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The Three Sludge System for Nitrogen and Phosphorus Removal

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by

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Advanced Waste Treatment Research Laboratory
Office of Research and Monitoring
Environmental Protection Agency

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ABSTRACT

The purpose of these studies was to evaluate the three sludge (carbon removal, nitrification and denitrification) system with alum addition for phosphorus removal. Eight months of performance data from a 0.2 mgd pilot plant, operating with diurnal flow variations over a nominal liquid temperature range of 10 to 20°C, are presented. Performance data for the soluble phase (COD, nitrogen and phosphorus), solids phase (solids characterizations and unit solids production values) and miscellaneous considerations (temperature, pH, alkalinity depletion, etc.) are presented.

Split chemical treatment with alum and optimum pH values will result in optimum system performance and the least amount of precipitated inorganic solids. Soluble phosphorus residuals as low as 0.1 mg/l can be easily achieved with an additional inorganic solids production of about 40 to 60 mg/l.

Key Words: wastewater treatment, activated sludge, carbon removal, nitrification, denitrification, phosphorus removal

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THE THREE SLUDGE SYSTEM FOR NITROGEN AND PHOSPHORUS REMOVAL*

by

M. C. Mulbarger**

Regulatory agencies are requiring municipal wastewater treatment facilities to achieve increased removals of carbonaceous and nitrogenous oxygen demands, suspended solids, nitrogen and phosphorus. These treatment requirements can be met by combinations or complete utilization of the unit process principles contained in the three sludge system (carbon removal, nitrification and denitrification). Previous investigations at the Manassas Field Station have shown that the three sludge system provided the most consistent performance for nitrification and denitrification and a superior removal of soluble carbonaceous oxygen demand (1). This system is also compatible with metal salt addition for phosphorus removal. In the Manassas studies, liquid alum was found to have a higher benefit -- cost ratio than either aluminate or ferric chloride (2). To transfer the three sludge system from a developmental stage to a process design stage, the treatment scheme originally proposed by Barth, et al (3), was evaluated on a sustained, optimized basis. The results reported provide eight months performance data from a 0.2 mgd (760 cum/day) pilot plant operating with diurnal flow variations over a nominal temperature range of 10 to 20°C.

FACILITY

The Manassas pilot plant was built above ground, fully exposed to local climatic conditions, to obtain maximum applicability of the study's results. Both of the aerators and the denitrification reactor were compartmentized to allow variation in the hydraulic detention times for long-term investigations. The pilot plant received screened, shredded, and degritted wastewater from a common wet well which it shared with a larger [1.0 mgd (3780 cum/day)] wastewater treatment plant. The pilot plant's final effluent was returned to the main plant's chlorine contact tank prior to final discharge. Figure 1 shows a recommended flow schematic for the three sludge system; it will be discussed in more detail in later sections. The Manassas pilot plant used this flow diagram with the addition of a flash mixer located just before the denitrification reactor and excluding the chlorine disinfection tank and post aeration system.

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THEORY

Table 1 summarizes the biochemical and physical-chemical reactions which can occur in the three sludge system. Detailed discussions of biological carbon removal (4)(5), nitrification (6), denitrification (7), and undesirable phosphorus release (8) are available in the literature. Similarly, more detailed discussions of the physical-chemical reactions can be found in basic reference books (9,10) or, in the case of complex calcium phosphate precipitation, in a recent publication (11). Heterotrophic carbon oxidation and endogenous respiration occur in both the high rate and denitrification systems with net nitrogen and phosphorus removal by synthesis. In the nitrification system, endogenous respiration and autotrophic synthesis by Nitrosomonas and Nitrobacter dominate. Biochemical hydrolysis of nitrogen and phosphorus in the high rate system converts most of the nitrogen to the proper form for synthesis and nitrification and most of the phosphorus to the ideal form for precipitation. In the absence of any usable industrial waste, methanol was selected as the driving carbon substrate for denitrification because of its cost, and because it is preferentially oxidized rather than synthesized.

The added aluminum is either hydrolyzed to aluminum hydroxide or precipitated as aluminum phosphate. Some phosphorus removal can also occur by sorption upon the aluminum hydroxide floc. These reactions are largely pH dependent. Acid pH values and anaerobic conditions may promote bacterial release of phosphorus (8). Coagulation of effluent suspended solids and the positively charged aluminum-hydroxy-phosphate colloid can be achieved by the addition of an anionic polymer. Aeration can cause a pH rise in a biological system in the presence of minimal microbial carbon dioxide production by free carbon dioxide stripping.

The nitrification reaction causes an alkalinity depletion which may have to be compensated for by lime addition in a poorly buffered wastewater. Sulfuric acid addition can be incorporated to deplete the wastewater's alkalinity and adjust the pH to the optimum range for phosphorus removal. A more detailed discussion of these reactions, much of it based upon hindsight after observation, will be included in the appropriate sections of this article.

OPERATION AND TECHNIQUES

Diurnal variability in the pilot plant was achieved by two pumps which were operated from 8 a.m. to 4 p.m. during dry weather conditions and were in continuous operation during periods of heavy infiltration or storm runoff. The return sludge or recycle rates (R) desired were calculated daily from the following relationship:

$$R = Q_{max} \left(\frac{MLSS}{\frac{10^6}{SVI} - MLSS} \right)$$

Where: MLSS = mixed liquor suspended solids
SVI = sludge volume index
Qmax = 200 gpm (12.6 l/sec)

This relationship gives a conservative recycle rate and assures that the system is in mass equilibrium. Table 2 summarizes the average hydraulic conditions for the eight-month period. The maximum and minimum influent flow values are the average four-hour maximum and minimum. During the study, approximately 40 percent of the study days were with heavy infiltration. The detention times in the reactors were close to optimum in every instance except in the case of the denitrification reactor, where a detention time of 0.5 to 0.8 hours could have been used. Piping limitations prevented the use of a smaller detention time in this unit process.

The high rate activated sludge system was operated with a cell residence time (CRT) (5) of 2 ± 1 days with sludge wasting each morning. The nitrifying and denitrifying systems were operated in a desired range of MLSS with sludge wasting whenever the range was exceeded. All chemical additions (aluminum, methanol, sulfuric acid, and polymer) were manually set as a function of expected wastewater quality and quantity.

Figure 2 shows the monthly variation in influent flow and the liquid temperature in the nitrification system. Liquid temperatures in the high rate activated sludge and denitrification systems were normally within $\pm$ 1°C of that measured in the nitrification system. Temperatures and dissolved oxygen levels (lead-silver electrode) were measured daily around noon; this was assumed to be the average 24-hour temperature and the worst time for aerator dissolved oxygen. Average monthly dissolved oxygen concentrations in the nitrification system were not allowed to drop below 3.0 mg/l and ranged from 0.4 to 0.1 mg/l in the denitrification system. As indicated in Figure 2, heavy storm flows were received in November, January, February, May, and June.

Each investigation was a 25-day study. The study periods can be summarized as follows:

November and December:	Split liquid alum addition
January and February:	Preceding plus sulfuric acid addition to establish optimum pH values for phosphorus removal
March through June:	Preceding plus polymer addition for effluent solids control

At the beginning, three times during, and at the end of each study period, the solids in grab samples from the aerators were analyzed in detail for volatile fraction and nitrogen and phosphorus content. Weekly proportional composites of the waste sludge streams were also analyzed. Flow proportional samples of the main stream were collected every two hours and added to a refrigerated 24-hour composite. Sampling times were not staggered because of the long investigative period. Samples were separated into total

and soluble fractions by filtration through a Whatman No. 5 filter. Pollutants in the solid phase were then determined by the difference between the soluble and total sample analyses. This was done so that reactor performance could be separated from the efficiency of the clarifiers. Mass balances were utilized in all of the studies to check analytical validity and to measure unit solids production values.

Periodically during the eight month investigation, time dependent profiles were run through the compartments of the nitrification and denitrification systems to determine reaction rate dependency upon liquid temperature. Sludge settling characteristics of the mixed liquor suspended solids from each system were also periodically determined in a one-liter graduate.

All main stream analyses from the 25-day studies were conducted with a 24-hour daily or three day weekend composite except ammonia, nitrite and nitrate determinations; these analyses were always conducted daily with the 24-hour composite to minimize sample change with time. All phosphorus values are for total phosphorus as determined after potassium persulfate and acid addition (12). Volatile solids measurements were done by standard techniques and with an acid pretreatment step [0.2N HCl added dropwise to pH 2, 10 minutes mixing, filtration, conventional drying and ashing (13)] to release any chemically bound water associated with precipitated aluminum hydroxide. Also reported are the conventionally determined and the nonacid soluble volatile fractions of MLSS samples. Brucine nitrate nitrogen and all other analytical procedures followed Standard Methods (14).

RESULTS

There are three fundamental factors which control the rate of an enzymatic or biological reaction: pH, temperature and substrate concentration. Michaelis-Menten kinetic models have been used to represent the removal of carbonaceous (4)(5) and nitrogenous (15)(16)(17) substrates. In a municipal wastewater there is essentially no control over the incoming substrate concentration and, hence, no means of optimization by substrate manipulation.

pH

Figure 3 shows the pH compatibility diagram, using non-acclimated cultures, for biochemical carbon removal (an assumed range of 6 to 8), nitrification (18), denitrification (measured with batch studies at Manassas), and phosphorus removal with aluminum addition (2). Manassas experience indicates that nitrification may be broader based than that reported in Figure 3. Indeed, Haug and McCarty (6) report no attenuation of nitrifying organisms at pH 6 after sufficient acclimation but, on the other hand, Rimer and Woodward (19) found nitrification difficulties if the system's pH dropped much below 8. Figure 3 indicates that nitrification and phosphorus removal by alum addition cannot be optimized simultaneously (with

the qualification of nonacclimated cultures). Long, et al (20), reported nitrification attenuation when alum addition to a lowly buffered wastewater depressed the pH to values near optimum for phosphorus removal.

The three sludge system allows biological culture optimization, if it is necessary. Here the ideal point of alkalinity-dependent sulfuric acid addition is at the beginning of the aeration channel following the denitrification reaction. This assures maximum alkalinity depletions due to alum addition in the first stage system and nitrification in the second stage system and allows a natural pH adjustment in the denitrification reactor by the return sludge volume.

Isolation of the nitrification system allows natural favorable pH adjustments or the addition of lime to more ideal values in a poorly buffered wastewater. The substantial alkalinity depletion which occurs during nitrification can cause a theoretical pH depression but, in well buffered wastewaters such as at Manassas, a pH rise of 0.1 to 0.3 units is measured. This is due to carbon dioxide stripping, carbon dioxide utilization by the autotrophic nitrifying bacteria, and minimal microbial carbon dioxide production because of the dominance of endogenous conditions in an isolated nitrification system. The Manassas nitrification system operated at a pH of 7.8 $\pm$ 0.2.

Temperature

The dependence of the nitrification and denitrification systems on temperature is shown in Figures 4 and 5. Examination of the soluble COD values from the high rate system for the four coldest months of operation against the four warmest months showed no temperature dependency with effluent values more dependent on the presence or absence of infiltration.

Nitrification and denitrification rate temperature relationships were determined from a least squares curve fit of the data points. Maximum and minimum observations were used to define the performance envelope. Since the majority of the observations fall between 10 and 20°C, this defines the range of applicability. These rates are higher than previously reported (1) and this is attributed to freedom from inhibiting industrial wastes, more optimum pH values, and long-term existence of isolated cultures. Temperature coefficients or Q_{10} (Y_{20}/Y_{10}) values of 2.2 and 5.0 were found for the nitrification and denitrification systems respectively. Although a Q_{10} value of 2 is typically defined for wastewater treatment organisms, widely varying temperature coefficients are reported for enzymatic cell processes (21).

In the absence of other information, the author's recommendation is that all unit processes should be designed at the average anticipated four-hour dry weather peak flow. Design of the nitrification and denitrification reactors should be at the average minimum monthly temperature using the reaction rates reported in Figures 4 and 5. The reciprocal of

the rates determines the system's minimum allowable cell residence time (5); longer cell residence times, if attainable, will increase the number of available nitrifying or denitrifying organisms and decrease the residence time required.

Substrate Concentration

The Manassas wastewater is highly mineralized and alkaline. Dissolved solids and sulfate concentrations in the water supply exceed recommended drinking water standards (22). About 40 percent of the time the treatment plant operates under severe infiltration conditions. Periodically, the receiving creek would flood its banks and transfer heavy quantities of mud into the treatment system. Table 3 shows the influent and primary effluent quality for the 200 24-hour flow proportional composite samples. The recycle of poor digester supernatant from the main plant to the wet well and thus to the pilot plant is indicated by comparing influent and primary effluent TKN values. The normal main plant practice was to waste to the digester during the low flow, early morning hours. During dry weather conditions, the pilot plant takes the majority of the flow and thus, received a disproportionate amount of supernatant over the normal two-hour period that it is received in the wet well. Occasionally, the supernatant would turn the pilot plant's primary clarifier black and cause a peak soluble unoxidized nitrogen concentration (in grab samples) of up to 60 mg/l to be applied to the nitrification system.

SOLUBLE PHASE

COD Removal

Figure 6 shows a frequency distribution of the soluble COD determinations in the high rate, nitrifying and denitrifying activated sludge effluents. BOD_5/COD ratios are the average, maximum and minimum monthly values; no attempt was made to stop nitrification during the BOD determinations.

In the treatment of domestic wastewaters, several investigators, most recently Rickert and Hunter (23), have shown that in a single activated sludge system a stable soluble organic residual is found after aeration times of 30 to 60 minutes. This observation was made at Manassas; and, with the derived sludge stability from aluminum addition, a minimum hydraulic contact time of one hour based on the four-hour dry weather peak flow and a cell residence time of 2±1 days are recommended for the high rate system (2). Some soluble organic removal may also be derived from aluminum addition, that is, metal salts can form insoluble compounds with protein and protein degradation products (9), but a conservative design would take no credit for this. Eighty percent of the high rate system's soluble COD's were 40 mg/l or less.

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The nitrification system achieves additional soluble COD removal. The older mixed culture in the nitrification system apparently develops an enzymatic capability to break down some of the more biologically resistant organic compounds found in domestic wastewater. Ninety-three percent of the nitrification effluent's soluble COD's were 30 mg/l or less--an extremely stable effluent in terms of carbonaceous oxygen demand.

Six investigative days were lost in the denitrification system due to a broken belt on the return sludge pump. A greater instability is found in the denitrification system, with its soluble COD exceeding that of the nitrification system 43 percent of the time, although it exceeded the value found in the high rate effluent only once. This instability is not due to the biological system but rather to the physical limitations of the pilot plant's operation. The higher effluent COD values result from an excess of methanol. Manually setting methanol addition based upon previous plant performance leaves something to be desired when attempts are being made to simultaneously maximize nitrogen removal and minimize soluble effluent COD's. The vast majority of the extreme over additions of methanol occurred during an acid kill of the denitrification system in January (pH < 4) and an acid attenuation (pH < 5) in February due to a lack of automation on acid feeds for optimum phosphorus removal. Recovery in January and February took 16 and 10 days respectively, or about 13 percent of the total determinations. Minimization of the soluble COD of the denitrification effluent can only be assured by underdosing the methanol (not attempting to maximize denitrification performance) or by proper instrumentation which automatically feeds the methanol as a function of the mass flow of nitrate nitrogen applied to the denitrification system. The AutoAnalyzer and Orion Nitrate probe are two instruments which have possible applicability.* The AutoAnalyzer has been successfully applied for this application (24).

Phosphorus Removal

Figure 7 is the frequency diagram of soluble total phosphorus concentrations in the pilot plant's process streams. The higher values all occurred in the final two weeks of operation when alum was in short supply. Chemical feed pumps also froze up several times during winter operation but never more than 12 to 16 hours at any one time. Those results above ninety percent in Fig. 7 can be attributed to freezing or the final two weeks of operation.

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*Mention of specific proprietary products or equipment here and elsewhere in the text is for information purposes only and does not constitute endorsement by the Office of Research and Monitoring and the Environmental Protection Agency.

The high rate activated sludge effluent shows a median soluble total phosphorus concentration of 2 mg/l at an average aluminum to primary effluent phosphorus ratio of 1/1. Table 4 summarizes the monthly results. A previously measured background phosphorus removal rate of 0.01 pounds of phosphorus per pound of COD removed (2) was assumed constant and used throughout this investigation. Alum was added to the tail end of the aerator to provide more efficient chemical use by assuring phosphorus hydrolysis to orthophosphate and minimizing competing side reactions (2). Chemical addition at this point can also take advantage of a pH decline due to alum addition (20) and prevent phosphorus resolubilization due to over aeration (25).

Half of the daily alum requirement was fed during the peak 8 a.m. to 4 p.m. flow period during November and December. No measurable performance difference could be found when a constant alum dose was applied over a 24-hour period in January and February. Thus, for the remaining four months of operation, constant chemical doses were applied and changed only with the presence or absence of infiltration.

A more meaningful plot of the data is shown in Figure 8 which describes the chemical phosphorus removal envelope for the high rate system both for these studies and previous investigations with aluminate (2). As will be shown later, this curve can be used not only to predict performance but also to closely predict the magnitude and form of inorganic solids produced as well as the alkalinity depletions derived from alum addition. By replotting the envelope in Figure 8 with an assumed phosphorus remaining of 10 mg/l, Figure 9 is produced. This Figure shows a rapid leveling off of performance once aluminum to phosphorus ratios of 1/1 are exceeded with no significant benefit derived from dosing above a ratio of 1.5/1 lb/lb. This curve points out that system performance is limited by pH dependent solubility products.

Again referring to Figure 7, a consistent soluble phosphorus reduction is measured through the nitrification system. This is thought to be due to the formation of an insoluble calcium phosphate complex which may accompany a pH rise with the mineralized Manassas wastewater (11), although it may be due to further utilization of aluminum-hydroxy-phosphate floc carried over from the high rate system. A conservative design would not take any credit for phosphorus removal in this unit process.

The two techniques for optimum phosphorus removal at minimum chemical dose are pH adjustment (at Manassas, pH conditions of 6 to 6.5 resulted in $CaCO_3$ alkalinity values of 20 to 40 mg/l) and split or multiple chemical additions. Figure 7 shows the soluble effluent phosphorus values found in the denitrification effluent during the six months of sulfuric acid addition. Elimination of all data points except those where the pH in the aerated channel effluent was between 6 and 6.5 and where the alum to phosphorus remaining (soluble phosphorus in the nitrification effluent) dose was 1/1

or more, produced the performance curve shown in Figure 10. This Figure shows that essentially complete phosphorus removal can be obtained at optimum pH values if one wants to pay the chemical price. Long, et al (20), shows a similar curve where alum addition to a single sludge system caused a pH decline to near optimum values for phosphorus removal. Split treatment allows the aluminum to phosphorus driving force to be substantially increased in the second stage for minimal chemical expenditures and results in the least amount of additional solids production. Split treatment could be practiced in combinations of primary and biological carbon removal or filtration systems. It should be noted, however, that batch studies at Manassas indicated that soluble effluent phosphorus residuals of less than 1.0 mg/l may be difficult to achieve with optimized pH values when working with just primary or biologically stabilized effluents (2). Alum addition to the aeration channel was applied at a constant, 24-hour feed rate. Acid addition was manually set. For phosphorus removal dependability as well as to protect the denitrification culture acid addition in every instance should be automatically controlled as a function of a continuous pH measurement in the aeration channel. If an extremely low phosphorus residual (0.5 mg/l) is desired, alum addition should be applied as a function of the mixed liquor flow. As discussed later, about five minutes of mix time (based on the average four-hour peak Q) should separate the sequential addition of acid, alum and polymer.

Acid pH and the absence of dissolved oxygen have been reported as causing phosphorus release from the solid phase (8). This was checked for on five different 24-hour runs: in no instance was the measured soluble phosphorus concentration after acid addition higher than what would be predicted from the blending of nitrification effluent and return sludge soluble phosphorus levels; the accountability averaged 104 percent. If phosphorus release does occur in this system, it is apparently compensated for by background phosphorus removals associated with the oxidation of methanol during denitrification.

Nitrification and Nitrogen Removal

The distribution of soluble nitrogen forms in the pilot plant's effluents are shown in Figure 11. TKN values are shown for the high rate effluent since organic nitrogen hydrolysis to ammonia is normally only 70 to 80 percent complete in the short detention times used in the high rate activated sludge system. For clarity, soluble organic nitrogen values in the nitrification and denitrification effluents are not shown. Normally, they run between 0.4 and 1.8 mg/l and average about 1.0 mg/l.

In designing a system for nitrification and denitrification, the high rate system provides a positive benefit by removing some of the incoming nitrogen by synthesis (about 0.05 pounds of nitrogen per pound of COD removed). This allows a reduction of nitrification and denitrification contact times and minimizes methanol requirements. Oxidized nitrogen was

measured in the high rate effluent for 197 of the 200 determinations. This is attributed to the wasting of denitrifying activated sludge to the primary clarifier where the high surface overflow rates did not allow complete solids capture. Denitrifying activated sludge also contains "sloughed" nitrifiers from the nitrification system. Instability of nitrifying systems would be indicated by nitrite nitrogen in the system effluent; nitrite nitrogen was occasionally measured in the high rate effluent but never above trace quantities in the nitrification and denitrification effluents. Nitrification temperature dependency is also illustrated by the high rate system's performance. Forty-nine of the top fifty nitrate measurements and thirteen of the lowest fifty measurements were associated with the four warmest months of operation.

Performance of the nitrification system is judged on ammonia breakthrough in the process effluent. At Manassas, 77 percent of the determinations showed no ammonia breakthrough while 90 percent of the measurements were 2 mg/l or less. All of the ammonia breakthroughs except one or two during the coldest months coincided with high, unproportional recycles of digester supernatant during dry weather operation. This points out the need to consider minor process recycle changes. Ideally, the supernatant should be returned continuously to avoid substantial slugs. Those processes which cause a substantial solubilization of solid phase nutrients, that is, heat and pressure sludge conditioning, demand special considerations in basic plant design. The nitrification system should be designed to nitrify the total nitrogen (soluble and solid phase) contained in the high rate effluent; no credit should be taken for nitrification in the high rate effluent with a conservative design.

Ammonia breakthrough from the denitrification system is always less than that measured from the nitrification system. This is due to dilution in the denitrification tank as well as additional polishing nitrification in the aeration channel due to "sloughed" nitrifiers in the denitrifying activated sludge. No ammonia breakthrough occurred in 87 percent of the determinations while 90 percent of the values were 0.5 mg/l or less.

An average methanol supply to theoretical methanol demand (dissolved oxygen and nitrate nitrogen requirements) of 1.5 was used for the eight months of investigation. This produced a nominal effluent nitrate nitrogen concentration of about 1.0 mg/l. In the many profiles through the denitrification reactor, the measured nitrite nitrogen concentration never rose above trace levels. If the denitrification reaction did stop at an intermediate point, however, the nitrite nitrogen would be oxidized back to nitrate in the aeration channel. The denitrification tank surface was exposed throughout the study; investigations in the summer of 1970 with a closed tank showed immeasurable changes in system kinetics. Performance instability was due to the acid kill and attenuation of the system (about 13 percent of the determinations) and under-dosages of methanol. Manual setting of methanol addition as a function of historic performance could

take care of flow variations but could not anticipate the diurnal change of nitrate nitrogen in the nitrification effluent (an approximate two-fold change between daily highs and lows (1) and the absence or presence and magnitude of digester supernatant returns. Consistent high-level nitrogen removal can be assured only by automation of the methanol feed. With automation, oxidized nitrogen residuals of 1.0 mg/l or less should be found in the effluent. Other than this, the total nitrogen removal efficiency would be limited only by the nonbiodegradable soluble organic residual, which varies between 0.4 and 1.8 mg/l.

SOLID PHASE

Solids Production

Table 5 shows the performance of the three biological systems. Average, maximum and minimum monthly values are reported. Phosphorus and nitrogen mass balances are also reported to verify the measured observations. Cell residence times in days were calculated by dividing the total pounds of solids under aeration by the pounds of solids wasted and lost in the effluent per day.

In comparing the nitrogen and phosphorus mass balances in the high rate and nitrifying activated sludge systems, one will notice that the nitrogen mass balances are consistently higher. This is attributed to errors in brucine nitrate nitrogen determinations which apparently read high. The consistently high phosphorus mass balance in the denitrification system is indicative of an error in process control; in this case it appears the waste sludge instrument reads erroneously high. Generally, however, excellent accountability of phosphorus was achieved.

The acid pretreatment step prior to the volatile solids determinations gave reasonably rational net solids production values for a high rate activated sludge system treating settled domestic wastewater. The unit net solids production rate for the denitrification system is essentially due to methanol (1.5 lbs COD/lb MeOH) oxidation and shows the expected minimal net synthesis. Performance of the nitrification system was found to be temperature dependent showing a net solids accumulation in the winter and a net solids destruction in the warmer months; the breakpoint appeared to be a liquid temperature of about 12°C. The nitrification system is similar to an aerobic digester and its effluent, although reasonably low in suspended solids and highly oxidized, generally lacks the clarity associated with a well operated, standard rate activated sludge plant.

Previous investigations have noted an additional inorganic solids production of about four pounds of inorganic solids per pound of aluminum added with stoichiometric aluminum to phosphorus remaining dosages. Unit solids production rates decline as the stoichiometric dosage is exceeded (2). The magnitude and character of the additional inorganic solids produced

from aluminum addition vary as a function of the pH, phosphorus removal, and aluminum dosage. They can be predicted with reasonable accuracy from Figure 8 (performance envelope for neutral to alkaline pH values) or Figure 10 (performance envelope for optimum pH conditions) and the two competing pH dependent alum reactions (hydrolysis and precipitation) given in Table 1. An illustrative example, using the Manassas data in Table 4, is provided below:

An average chemical phosphorus removal of 0.64 pounds per pound of aluminum added was measured. Therefore, the chemical phosphorus removal was:

$$(7.9 \text{ mg/l } Al^{+3})(0.64 \frac{\text{mg/l P}}{\text{mg/l } Al^{+3}}) = 5.0 \text{ mg/l P} \quad (1)$$

This would produce an additional solids production of:

$$(5.0 \text{ mg/l P})(3.9 \frac{\text{mg/l } AlPO_4}{\text{mg/l P}}) = 20 \text{ mg/l } AlPO_4 \quad (2)$$

and use:

$$(5.0 \text{ mg/l P})(0.87 \frac{\text{mg/l } Al^{+3}}{\text{mg/l P}}) = 4.4 \text{ mg/l } Al^{+3} \quad (3)$$

Therefore:

$$(7.9 - 4.4 \text{ mg/l } Al^{+3}) = 3.5 \text{ mg/l } Al^{+3} \quad (4)$$

is left and available for hydrolysis which would produce an additional solids of:

$$(3.5 \text{ mg/l } Al^{+3})(2.9 \frac{\text{mg/l } Al(OH)_3}{\text{mg/l } Al^{+3}}) = 10 \text{ mg/l } Al(OH)_3 \quad (5)$$

Therefore an additional solids production of 30 mg/l is predicted (actual solids production will be somewhat less due to phosphorus "sorption" on the aluminum-hydroxy colloid).

This calculates to be:

$$\frac{30 \text{ mg/l inorganic solids}}{7.9 \text{ mg/l } Al^{+3}} = 3.8 \text{ pounds of additional solids produced per pound of aluminum added} \quad (6)$$

Using similar calculations, an additional 5 mg/l of $AlPO_4$ and 6 mg/l $Al(OH)_3$ can be calculated as being formed during the final four months of operation in the Manassas denitrification system. Previous measurements have shown trace to 0.3 mg/l soluble aluminum in the process effluents (2). Therefore, a total calculated additional inorganic solids mass of about 41 mg/l was produced.

Experience with two stage lime treatment (26) and a comparison of the molecular weights of aluminum (27 gram moles) and iron (55.8 gram moles) leads to the conclusion that optimized, split treatment with aluminum will produce the least amount of additional solids for ultimate disposal: probably 50 to 70 percent of that found with iron and 5 to 20 percent of that associated with two-stage lime treatment.

Solids Characteristics

Table 6 characterizes the solids on an average, maximum, and minimum monthly basis for the three sludge system. Only the final four months from the denitrification system are presented since until that time it was not completely optimized.

Examination of the reactor solids shows that an easily settleable and dense sludge results from alum addition. Experiences with nitrification inhibiting industrial wastes caused severe bulking (SVI's > 200 ml/gm) in the main plant but went relatively unnoticed in the pilot plant's operation due to the metal salt additions. The nonacid soluble MLVSS are quite low in each system which indicates the accumulation of inorganic solids. Background measurements in the high rate and denitrification system prior to chemical addition showed mixed liquor volatile fractions of about 75 percent.

The pollutant characterization of the effluent suspended solids is provided to allow the prediction of total process stream quality and to show what improvement can be derived by effluent suspended solids control. For example, effluent suspended solids of 20 mg/l would add over 1 mg/l each of nitrogen and phosphorus to each of the process streams.

An indication of a tendency toward inorganic and organic solids classification (high nitrogen values assumed to be indicative of biological solids) is apparent by comparing reactor, effluent, and waste solids, even with the recognition that baseline solids measurement techniques are changing (MLSS-Whatman No. 1 paper, SS-glass fiber filters, TS-total solids). However, in almost two years of operation -- the last year almost completely with a combined chemical-biological system -- this apparent "sloughing" of biological solids in the effluent has not caused any noticeable process effect.

Figures 12, 13, and 14 show the physical characteristics of the activated sludge from each of the sludge systems. The denitrifying activated sludge data are only for the final four months of optimized performance. Samples were analyzed in the laboratory immediately after collections. These figures indicate that the denitrification system has the greatest stability and the nitrification system the least. Metal salt addition causes the activated sludge solids to settle rapidly until hindered solids separation is reached. The settling data has a built-in safety factor since they were determined in standard one liter graduates;

the reader should refer to several basic discussions of the limitations of these data (27)(28)(29). However, in the absence of other information, the data from these figures can be used to conservatively size clarifiers and solids pumping equipment.

Using average four-hour peak dry weather flows and the design MLSS, intermediate clarifiers (the high rate and nitrification system) may be sized for the average solids settling rate. The final clarifier should be sized at the minimum solids settling rate. A standard effective surface water depth is twelve feet (3.7 m). Conservative return sludge concentrations in mg/l can be calculated by dividing the highest SVI into 10^6. Return sludge capability should be calculated at the peak flows. Ideally, sludge wastage should be continuous. A $\pm$ 50 percent variation capability of the calculated return and waste sludge pumping capability should be provided to give operational flexibility.

Effluent Suspended Solids

The magnitude of effluent suspended solids determines treatment success or failure. Figure 15 shows the effluent suspended solids from each of the process streams. Extremely high values are encountered whenever the solids handling capability (return sludge pumping or surface overflow rate) is exceeded.

Successful operation of the nitrification system requires successful capture of mixed liquor solids in both the high rate and nitrifying system clarifiers, generally this is thought to be about 20 to 30 mg/l of effluent suspended solids. Sustained discharges of 40 to 50 mg/l or higher from either system could cause an abnormal loss of nitrifying organisms and attenuate nitrification performance.

The effluent suspended solids concentrations derived from 94 days of anionic polymer addition to the aeration channel before the denitrification settler are shown in Figure 15. The polymer addition system was not perfect (makeup, storage and feed from the same tank with constant chemical addition over a 24-hour period) but remarkable effluent quality improvements resulted. Nalco 676 was used at dosages of 0.3 to 0.5 mg/l on a product water basis. Ideally, one would want to dose on the mixed liquor flow at an apparent near optimum rate of 0.0001 pounds of polymer per pound of MLSS. Polymer performance was also pH dependent; appearing visually optimum at pH 6.5. In laboratory evaluations, Atlas 2A2 performed similarly at equivalent dosages and pH values. Effluent suspended solids greater than 5 mg/l occurred whenever the pH in the aeration channel effluent (the point of polymer addition) was outside of the 6.5 $\pm$ 0.5 range or on weekends when operator attention to polymer makeup and feeding was reduced. The 50 percent value of 2 mg/l effluent suspended solids is considered representative of optimized system performance. Again, based on the average dry weather four-hour peak flow, five minutes of contact time should separate the alum and polymer additions.

Previous investigations with aluminate have shown that the presence or absence of effluent suspended solids which are difficult to separate is more a function of the ratio of the biological volatile solids produced to aluminum added (it should not drop below 3 to 5 based on Manassas experience) than of the aluminum to phosphorus ratio or aluminum dose (2). This is thought to be due to the negatively charged biological floc which should have an affinity for positively charged aluminum-hydroxy-phosphate colloids. Once the "sorption" or exchange sites of the biological floc are exceeded, however, effluent suspended solids problems should occur. This would explain the observation of effluent turbidity increasing with progressively higher aluminum additions. In the denitrification system, with very little solids synthesis due to methanol addition, the allowable aluminum dose is only about 1 mg/l. Although alum addition improved effluent clarity in comparison to the previous investigations with aluminate (2) even pH control did not help the effluent suspended solids. As shown in Table 7, only polymer addition could achieve the remarkably low effluent suspended solids. It is the writer's opinion that every plant contemplating phosphorus removal by metal salt addition should include the capability of polymer addition should effluent suspended solids become a problem.

It is recognized that all systems may not be ideal at all times and final effluent filtration studies were conducted with small 4-inch (10 cm) diameter filters loaded at a constant 3 gpm/sq ft (122 $\frac{l/m}{sq\ m}$). In January a dual media filter [18 inches (46 cm) of anthracite and 6 inches (15 cm) of fine sand backed with 6 inches (15 cm) of coarse sand -- 90 percent sieve analysis of 0.9 mm, 0.45 mm, and 1.0 mm, respectively] reduced the nominal effluent suspended solids from 30 to 17 mg/l with an average filter run of 64 hours to eight feet of head loss. The backwash requirement was 2.2 percent of the feed. In February a mixed media filter was installed with the assistance of the manufacturer's representative. After a two-week filter ripening and conditioning period, effluent suspended solids were reduced from 34 to 6 mg/l with similar filter run and backwash measurements. These comparative runs indicated that the mixed media system provided superior suspended solids removal efficiencies and offered greater backup support to the combined chemical-biological three sludge system.

The final four months of operation were conducted with the mixed media filter and because of the improved effluent quality derived from polymer addition, average filter runs were increased to 133 hours and the backwash requirement dropped to 1.2 percent of the throughput. A frequency distribution of the effluent quality from the mixed media filter for the final four months of operation is shown in Figure 16. Each of the pollutant residuals is completely or largely independent of the influent wastewater quality. Although mixed media filtration does comparatively little for an optimized three-sludge system, its use is recommended as a positive backup support where consistently low pollutant residuals are the treatment requirement.

Solids Handling and Disposal

Previous investigations have noted that there was no phosphorus solubilization during anaerobic digestion, and the observation was made that digested solids dewatered better on sand beds than when no aluminum was added (2). It has also been noted that comparative bench dewaterability studies with settled high rate activated sludge with aluminum addition resulted in a substantial increase in yields (dry solids per unit time) but that the cake may contain a higher moisture content (2). A conservative design would use conventional loading rates for organic solids handling, although the data indicate that the increases in dry cake yields may fully compensate for the additional inorganic solids that must be handled at optimum aluminum dosages. The reported increase in dewaterability of aluminum-containing organic solids can probably be explained by the fact that straight waste activated sludge is notoriously difficult to dewater by itself and the additional inorganic solids produced by aluminum addition serve as a crude dewatering aide.

MISCELLANEOUS CONSIDERATIONS

Nitrification Inhibition

Evaluation of approximately four months of pilot plant performance was lost due to recurring problems with nitrification inhibiting industrial wastes. However, by identifying the causative agents and implementing protective operational procedures with industrial cooperation, a satisfactory resolution of the problem was achieved and successful project completion was obtained.

The problems at Manassas were caused by slug discharges of perchloroethylene, a halogenated solvent, which solubilized accumulations of abietic acid in the industry's sewer system. These periodic spills attenuated nitrification performance almost completely and caused sludge bulking and cellular destruction. Restored pilot plant operation with background perchloroethylene concentrations of 1 to 5 mg/l in the influent wastewater (31) was made possible by minimizing industrial spills and by increasing the aeration rate in the pilot plant's high rate system. Increasing the aeration rate effectively stripped out the volatile perchloroethylene and insolubilized abietic acid. The insoluble abietic acid was then trapped with the activated sludge solids and ultimately biodegraded or wasted from the high rate system. Complete protection, even during accidental spills in November and January, was obtained for the pilot plant's nitrification system by this operational modification until the industry's pretreatment system went into service in April. The reader is referred to the final contract report for more detailed information (30).

Manassas' experience shows the value of protecting the nitrification system with a buffering high rate activated sludge system.

Alkalinity Losses

Alkalinity losses in the three sludge system are derived from the nitrification reaction and alum addition. For eight months of operation, the average alkalinity loss through the nitrification system was 6.4 pounds of $CaCO_3$ alkalinity per pound of nitrate nitrogen produced, about 90 percent of the 7.1 lbs/lb theoretically predicted. The average measured alkalinity loss in the high rate system due to alum addition was 4.5 pounds of $CaCO_3$ alkalinity per pound of aluminum added. This alkalinity loss was about 80 percent of that predicted from the stoichiometric calculation.

In a lowly buffered wastewater, alkalinity depletion may be of sufficient magnitude to necessitate lime addition. Measured alkalinity losses indicate that alkalinity depletions can be conservatively predicted by the equations provided in Table 1. Similarly, assuming a residual alkalinity of 30 mg/l $CaCO_3$, the required sulfuric acid addition for optimum phosphorus removal with adjusted pH values can be calculated from the equation provided in Table 1.

Dissolved Solids Introduction

The great liability associated with metal salt addition is the introduction of dissolved solids which in some circumstances can be considered pollutants in their own right. Table 1 shows that about 5.4 pounds of sulfate are introduced per pound of aluminum when alum is the chemical of choice. It should be remembered, however, that the wastewater processes are also removing dissolved pollutants, i.e., organics, nitrogen and phosphorus. No gain in dissolved solids measurements, on an influent to final effluent basis was measured at Manassas until sulfuric acid addition was incorporated to maximize phosphorus removals.

Aeration and Mixing Requirements

The average oxygen uptake rate in the high rate system, measured during peak organic and hydraulic loadings, was about 80 mg per hour per gram of nonacid soluble MLVSS. A complete mix system is recommended since the pollutant to be removed (organic carbon) is both colloidal and soluble in nature.

Oxygen uptake rates in the nitrification system closely parallel the measured nitrification rate temperature dependency. Air application rates used in the nitrification system ranged from 1.1 cf/gal (8.2 l/l) in January to 1.8 cf/gal (13.5 l/l) in June. The shallow depth of the pilot plant's aerators make these application rates inapplicable to full-scale practice. From Table 1 it can be seen that other oxygen demands exist due to continued heterotrophic oxidation and endogenous respiration whereas the autotrophic organisms supply oxygen. A conservative design would supply oxygen at a rate equivalent to the nitrification rate at the warmest average monthly temperature multiplied by the stoichiometric

oxygen requirement for ammonia oxidation. Since ammonia nitrogen is a soluble pollutant, a plug flow aeration pattern with a minimum of three aeration compartments is recommended.

Similarly, the denitrification system should have a plug flow mixing pattern with a minimum of three reaction compartments. A minimum velocity gradient of 8-10 $\frac{ft/sec}{ft}$ with the capability to double this has been recommended from previous experience with the horizontal flocculators contained in the Manassas denitrification system (1). To preserve the flocculant nature of the mixed liquor solids, the velocity gradient in the aeration channel should not exceed 50 to 70 $\frac{ft/sec}{ft}$.

Chemical Addition

Special considerations for chemical storage, handling and application can best be answered by chemical suppliers. From a physical point of view, it is recommended that all chemical additions be applied to transferring or aeration channels rather than the aerator or reactor. This should help to preserve the flocculant nature of the chemical-biological solids. Flash mixing at the chemical addition points is not necessary. Acid, alum and polymer should be added sequentially with about five minutes of mix time between each application.

Clarifiers

Floating solids in the clarifiers due to denitrification did not occur in two years of operation. For conservative design, however, each clarifier should be equipped with skimmers. Floating solids from denitrification may be encountered in the high rate system's clarifier if high nitrification is occurring. Multiple point sludge collectors which work on a hydrostatic principle would be recommended for this system even though it is thought by some that they promote sludge classification into light and heavy fractions. The Manassas pilot plant uses single point sludge collection and similar systems would be recommended for the nitrification and denitrification clarifiers to avoid an exaggeration of sludge classification tendencies. A flocculator-clarifier should be considered for final solids-liquid separation to promote solids flocculation and effluent clarity.

Solids Wasting

The capability to feed waste high rate activated sludge to the nitrification and denitrification systems is recommended. This will aid plant startup, can aid effluent clarity and add new sludge to the nitrification system and may marginally reduce methanol requirements in the denitrification system. During the January acid kill, this capability greatly reduced system recovery time.

Partial nitrification in the high rate system has not been found to cause any physical or process effects. It is felt that achieving nitrification in this system provides additional plant nitrification capability and provides a warning system should a slug of inhibiting compounds be received at the plant. Therefore, a capability of wasting both nitrifying and denitrifying activated sludge back to the high rate activated sludge system is recommended. Since the denitrification system always contains some "sloughed" nitrifiers, a wasting capability back to the nitrification system is recommended to rapidly establish a higher concentration of nitrifying organisms.

A high surface overflow rate and short detention time in the primary clarifier will result in very little waste activated sludge thickening and some loss of waste solids back into the high rate system. In the design of larger plants, direct solids wastage to the solids handling and disposal system should be considered.

Spray Water

Foaming has not been a problem in the pilot plant's operation unless the MLSS in the high rate system drops below 2000-2500 mg/l. Spray water capability should be provided to all the aeration systems, however, to minimize startup problems.

Disinfection

The effluent from a three sludge system has essentially no chlorine demand due to biodegradable organics, suspended solids and nitrogen. This, plus the slightly acid pH, assures easy, effective disinfection at small chlorine dosages.

Costs

A detailed cost estimate can be very misleading, depending upon the knowledge and prejudices of the estimator as well as on local conditions. Certainly, with an advanced waste treatment process sequence, the only good capital estimate is the final bid. Generally, however, if a standard rate activated sludge plant with 4.5 to 6 hours aeration and complete solids handling is assumed as a standard baseline, a three sludge system should show the following incremental capital cost increases: two-stage treatment through nitrification, 5 to 10 percent; three-stage treatment through denitrification plus post aeration, 20 to 30 percent; mixed media filtration, 10 to 20 percent. Thus, capital expenditures for a three sludge system with mixed media filtration will be about 30 to 50 percent more than those for conventional activated sludge treatment. The cost of storage facilities, instrumentation, and chemical feed equipment should be relatively insignificant in comparison to the total plant bid at all but the smallest facilities. Power and maintenance expenditures should increase by about the same magnitude

as the capital expenditures. Actual manpower requirements will only be known after a full scale plant has gone on stream. However, since the majority of operational labor is spent in the primary and sludge treatment operations, and the isolated nitrification system essentially operates unattended, manpower requirements for the three sludge system should only marginally increase over conventional activated sludge plant operation. This increase will largely be associated with the chemical storage and feeding complex. Chemical costs are largely a function of the pollutant concentration and the required effluent residual. Chemical costs at Manassas for the final four months of operation were 6.1¢/1000 gallons, as follows:

Al^{+3} at \$0.32/pound = 3.0¢/1000 gallons
Nalco 676 at \$1.50/pound = 0.5¢/1000 gallons
Acid at \$0.02/pound = 0.7¢/1000 gallons
Methanol at \$0.05/pound = 1.9¢/1000 gallons

Operation

In the writer's opinion, the three sludge system is preferred over other biological nitrogen removal systems. The isolated cultures allow optimization with chemical addition and operation reduces to intelligent solids wasting. At Manassas, denitrifying sludge was wasted into the nitrification system in December to maximize the nitrifying population during the critical winter months. Higher operating solids concentrations were also used in the denitrification system during the winter. During the warmer spring months, operating solids were allowed to decline in the nitrification system and were lowered by wasting in the denitrification system.

At least one member of the plant's staff has to be knowledgeable in the unit process principles and reactions incorporated with the three sludge system receiving alum addition for phosphorus removal. As in any treatment process, the plant cannot be allowed merely to run but requires intelligent, knowledgeable and conscientious day-to-day operation.

Instrumentation

Automated methanol addition as a function of the mass flow of nitrate nitrogen is necessary to maximize the efficiency of the denitrification system; if not, lower methanol dosages will have to be used to avoid methanol breakthrough in the final effluent. Acid addition must be fully automated and pH controlled to avoid acid kills of the biological system, a pH range of 6 to 6.5 is recommended. If extremely low phosphorus residuals are required, alum addition should be flow dependent but a continuous measurement of incoming phosphorus concentrations is not thought to be necessary if enough background information on influent phosphorus concentration is available and ideal reaction conditions are consistently established. The most efficient use of aluminum is only obtained, however, by continuous measurement of phosphorus concentrations. Efficient usage of polymer is approached by flow dependent additions.

DISCUSSION AND CONCLUSIONS

The writer has tried to answer as many design and operational questions as possible with a detailed examination of a process sequence on one wastewater.

In the absence of other information, conservative design suggestions have been made, and it is felt that intelligent process design and satisfactory operation can be achieved with the data and suggestions presented. The data, of course, is limited and specific only for the Manassas conditions. Detailed design examples can be found elsewhere (30)(32).

The three sludge system incorporates biological treatment for sequential carbon removal, nitrification and denitrification; maximizing each in an isolated unit process which has the capability of buffering or protecting the preceding or subsequent system. The technology incorporated in this system can be transferred to existing treatment facilities or utilized for new facilities. It can meet existing and future discharge requirements by using staged construction and planning. Since chemical costs are largely a function of the pollutant concentration and the required treatment residual, it can meet changing influent pollutant concentrations and required treatment residuals. The aluminum precipitate serves as a weighing agent for the biological sludge, thus producing a denser sludge with faster settling characteristics. By combining biological with split chemical treatment, an effective blend of both which minimizes operational and solids handling problems, is achieved. Effective process design, chemical addition, and operation produces pollutant residuals completely or largely independent of raw wastewater. Mixed media filtration is recommended for its backup support when consistently low effluent pollutant residuals are required. Liabilities of the three sludge system center upon the addition of dissolved solids (sulfate), its inability to remove refractory organics, and the necessity of enforcing ordinances governing industrial discharge into municipal sewers to prevent slug discharges of inhibiting industrial wastes.

This treatment sequence does not offer the universal panacea to all nutrient removal problems in municipal wastewater treatment, but it does offer a valuable, workable alternative that combines and takes advantage of the most favorable attributes of physical, chemical and biological wastewater treatment. Table 8, a summary of the final four months of operation, clearly illustrates the excellent performance that can be achieved with the three sludge system. Specific conclusions other than those previously mentioned are:

1. Nitrification and denitrification rates are temperature dependent and, in nonacclimated cultures, pH dependent.

2. Phosphorus removal to a very low residual can be easily and economically achieved with split alum addition and pH optimization. The additional chemical solids production increases solids densities, settling rates and dewatering yields. The magnitude of solids production and alkalinity depletion derived from alum addition can be predicted with reasonable accuracy from phosphorus removal performance

envelopes and the stoichiometry of the pH-dependent alum hydrolysis and phosphorus precipitation reactions.

3. Superior removals of soluble COD and carbonaceous BOD_5 are obtained through the two-stage nitrification system and maintained through the denitrification system with proper methanol dosages.

4. Solids production values in the nitrification system are small or negative and temperature dependent.

5. The denitrification system shows an oxidized nitrogen value of 1.0 mg/l or less at methanol: nitrate nitrogen ratios of about 3:1. A soluble nonbiodegradable, organic nitrogen residual of about 1.0 mg/l limits and defines the maximum possible nitrogen removal efficiency. High level, dependable nitrogen removal performance and minimum effluent COD values are only assured by complete automation of methanol dosages as a function of the nitrate nitrogen mass flow.

6. Alkalinity dependent acid addition for pH optimization should also be automated for maximum system dependability.

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TABLE 1 - THREE SLUDGE SYSTEM REACTIONS

I. BIOCHEMICAL

A. Heterotrophic Oxidation

$$2(CH_2O)_x + N_y + P_g + O_2 \text{ -----> } [(CH_2O)_x \cdot N_y \cdot P_g] + CO_2 + H_2O$$

B. Autotrophic Oxidation

$$CO_2 + H_2O + N_y + P_g \text{ -----> } [(CH_2O)_x \cdot N_y \cdot P_g] + O_2$$

C. Endogenous Respiration

$$[(CH_2O)_x \cdot N_y \cdot P_g] + O_2 \text{ -----> } CO_2 + H_2O + N_y + P_g$$

D. Nitrification

1. Nitrosomonas

$$2\ NH_4^+ + 3\ O_2 \text{ -----> } 2\ NO_2^- + 4\ H^+ + 2\ H_2O$$

2. Nitrobacter

$$2\ NO_2^- + O_2 \text{ -----> } 2\ NO_3^-$$

3. Overall

$$2\ NH_4^+ + 4\ O_2 \text{ -----> } 2\ NO_3^- + 4\ H^+ + 2\ H_2O$$

(28 as N) (128)

or

4.6 pounds of oxygen required per pound of nitrogen oxidized

E. Denitrification with Methanol (CH_3OH)

$$6\ H^+ + 6\ NO_3^- + 5\ CH_3OH \text{ -----> } 5\ CO_2 + 3\ N_2 + 13\ H_2O$$

(84 as N) (160)

or

1.9 pounds of methanol per pound of nitrate nitrogen removed

F. Methanol Dissolved Oxygen Requirement

$$2\ CH_3OH + 3\ O_2 \text{ -----> } 2\ CO_2 + 4\ H_2O$$

(64) + (96)

or

0.67 pounds of methanol per pound of oxygen removed
one pound of methanol has a COD of 1.5 pounds
density of methanol = 6.6 pounds per gallon

TABLE 1 - Continued

G. Hydrolysis

1. Org N -----> NH_4^+

2. Complex P -----> PO_4^{-3}

H. Phosphorus Release

acid pH and anaerobic conditions may cause a release of phosphorus from the solid phase to the soluble phase

II. PHYSICAL-CHEMICAL

A. Alum Addition

1. Hydrolysis

$$Al_2(SO_4)_3 + 6\ HCO_3 \text{ -----> } 2\ AL(OH)_3 + 3\ SO_4^{-2} + 6\ CO_2$$

(54 as Al^{+3}) (300 as $CaCO_3$) (156) (288)

or

5.5 pounds of $CaCO_3$ alkalinity lost per pound Al^{+3} added
2.9 pounds of $Al(OH)_3$ produced per pound Al^{+3} added
5.4 pounds of SO_4^{-2} (dissolved solids) added per pound Al^{+3} added

2. Precipitation

$$Al_2(SO_4)_3 + 2\ PO_4^{-3} \text{ -----> } 2\ AlPO_4 + 3\ SO_4^{-2}$$

(54 as Al^{+3}) + (62 as P) (244)

or

4.5 pounds of $AlPO_4$ produced per pound Al^{+3} added
3.9 pounds of $AlPO_4$ produced per pound P removed
0.87 pounds of Al^{+3} removed per pound P removed

3. Sorption

$$(2\ Al(OH)_3 \cdot 2\ AlPO_4)^{+3}_{colloid}$$

B. Coagulation

$$(\text{Aluminum-Hydroxy} \cdot \text{Phosphate})^{+}_{colloid} \cdot (\text{anionic polymer})$$

TABLE 1 - Continued

C. Bicarbonate Equilibrium

$$CO_2 + H_2O \xrightleftharpoons{} H_2CO_3 \xrightleftharpoons{} HCO_3^- + H^+$$

1. Aeration-CO_2 or free carbon dioxide removal

   a. pH rise

   b. $[Ca_3(PO_4)_2 \cdot CaCO_3]_{complex}$ formation

D. Alaklinity Loss

1. Nitrification

$$4\ H^+ + 4\ HCO_3^- \longleftarrow 4\ CO_2 + 4\ H_2O$$
$$(4) \quad + (200)$$

or

7.1 pounds of $CaCO_3$ alkalinity loss per pound of nitrogen oxidized (ref. biochemical nitrification reaction)

E. pH Control

1. Sulfuric Acid Addition

$$H_2SO_4 + 2\ HCO_3^- \longleftarrow 2\ CO_2 + 2\ H_2O + SO_4^{-2}$$
$$(98) \quad (100) \qquad\qquad\qquad\qquad (96)$$

or

1.0 pounds of $CaCO_3$ alkalinity loss per pound of sulfuric acid added
1.0 pound of dissolved solids (SO_4^{-2}) added per pound of sulfuric acid added

2. Lime Addition

$$Ca(OH)_2 + 2\ CO_2 \longrightarrow Ca(HCO_3)_2$$
$$(74) \qquad\qquad\qquad (100 \text{ as } CaCO_3)$$

or

1.4 pounds of $CaCO_3$ alkalinity added per pound $Ca(OH)_2$ added

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TABLE 1 - THREE SLUDGE SYSTEM REACTIONS

I. BIOCHEMICAL

A. HETEROTROPHIC OXIDATION

$$2(CH_2O)_x + N_y + P_g + O_2 \longrightarrow [(CH_2O)_x \cdot N_y \cdot P_g] + CO_2 + H_2O$$

B. AUTOTROPHIC OXIDATION

$$CO_2 + H_2O + N_y + P_g \longrightarrow [(CH_2O)_x \cdot N_y \cdot P_g] + O_2$$

C. ENDOGENOUS RESPIRATION

$$[(CH_2O)_x \cdot N_y \cdot Pg] + O_2 \longrightarrow CO_2 + H_2O + N_y + P_g$$

D. NITRIFICATION

1. NITROSOMONAS

$$2\ NH_4^+ + 3\ O_2 \longrightarrow 2\ NO_2^- + 4\ H^+ + 2\ H_2O$$

2. NITROBACTER

$$2\ NO_2^- + O_2 \longrightarrow 2\ NO_3^-$$

3. OVERALL

$$2\ NH_4^+ + 4\ O_2 \longrightarrow 2\ NO_3^- + 4\ H^+ + 2\ H_2O$$

(28 as N) (128)

OR

4.6 POUNDS OF OXYGEN REQUIRED PER POUND OF NITROGEN OXIDIZED

TABLE 1 - THREE SLUDGE SYSTEM REACTIONS (CONT.)

I. BIOCHEMICAL (CONT.)

E. DENITRIFICATION WITH METHANOL (CH_3OH)

$$6\ NO_3^- + 5\ CH_3OH \longrightarrow 5\ CO_2 + 3\ N_2 + 7\ H_2O + 6OH^-$$

(84 as N) (160)

OR

1.9 POUNDS OF METHANOL PER POUND OF NITRATE NITROGEN REMOVED

F. METHANOL DISSOLVED OXYGEN REQUIREMENT

$$2\ CH_3OH + 3\ O_2 \longrightarrow 2\ CO_2 + 4\ H_2O$$

(64) + (96)

OR

0.67 POUNDS OF METHANOL PER POUND OF OXYGEN REMOVED
ONE POUND OF METHANOL HAS A COD OF 1.5 POUNDS
DENSITY OF METHANOL = 6.6 POUNDS PER GALLON

G. HYDROLYSIS

1. ORG N $\longrightarrow$ NH_4^+
2. COMPLEX P $\longrightarrow$ PO_4^{-3}

H. PHOSPHORUS RELEASE

ACID pH AND ANAEROBIC CONDITIONS MAY CAUSE A RELEASE OF PHOSPHORUS FROM THE SOLID PHASE TO THE SOLUBLE PHASE

TABLE 1 - THREE SLUDGE SYSTEM REACTIONS (CONT.)

II. PHYSICAL-CHEMICAL

A. ALUM ADDITION

1. HYDROLYSIS

$Al_2(SO_4)_3 + 6\ HCO_3 \longrightarrow 2\ AL(OH)_3 + 3\ SO_4^{-2} + 6\ CO_2$

(54 as Al^{+3}) (300 as $CaCO_3$) (156) (288)

OR

5.5 POUNDS OF $CaCO_3$ ALKALINITY LOST PER POUND Al^{+3} ADDED

2.9 POUNDS OF $Al(OH)_3$ PRODUCED PER POUND Al^{+3} ADDED

5.4 POUNDS OF SO_4^{-2} (DISSOLVED SOLIDS) ADDED PER POUND Al^{+3} ADDED

2. PRECIPITATION

$Al_2(SO_4)_3 + 2\ PO_4^{-3} \longrightarrow 2\ AlPO_4 + 3\ SO_4^{-2}$

(54 as Al+3) + (62 as P) (244)

OR

4.5 POUNDS OF $AlPO_4$ PRODUCED PER POUND Al+3 ADDED

3.9 POUNDS OF $AlPO_4$ PRODUCED PER POUND P REMOVED

0.87 POUNDS OF Al^{+3} REMOVED PER POUND P REMOVED

3. SORPTION

$(2\ Al(OH)_3 \cdot 2\ AlPO_4)^{+3}$ COLLOID

B. COAGULATION

(ALUMINUM-HYDROXY · PHOSPHATE)$^+$ COLLOID (ANIONIC POLYMER)

TABLE 1 - THREE SLUDGE SYSTEM REACTIONS (CONT.)

II. PHYSICAL-CHEMICAL (CONT.)

C. BICARBONATE EQUILIBRIUM

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$

1. AERATION–CO_2 OR FREE CARBON DIOXIDE REMOVAL
   a. pH RISE
   b. $[Ca_3(PO_4)_2 \cdot CaCO_3]$ COMPLEX FORMATION

D. ALAKLINITY LOSS

1. NITRIFICATION

$$4\ H^+ + 4\ HCO_3^- \longrightarrow 4\ CO_2 + 4\ H_2O$$

(4) + (200)

OR

7.1 POUNDS OF $CaCO_3$ ALKALINITY LOSS PER POUND OF NITROGEN OXIDIZED (REF. BIOCHEMICAL NITRIFICATION REACTION)

TABLE 1 - THREE SLUDGE SYSTEM REACTIONS (CONT.)

II. PHYSICAL-CHEMICAL (CONT.)

E. pH CONTROL

1. SULFURIC ACID ADDITION

$$H_2SO_4 + 2\,HCO_3^- \longrightarrow 2\,CO_2 + 2\,H_2O + SO_4^{-2}$$

(98) (100) OR (96)

1.0 POUNDS OF CaCO3 ALKALINITY LOSS PER POUND OF SULFURIC ACID ADDED

1.0 POUND OF DISSOLVED SOLIDS (SO_4^{-2}) ADDED PER POUND OF SULFURIC ACID ADDED

2. LIME ADDITION

$$Ca(OH)_2 + 2\,CO_2 \longrightarrow Ca(HCO_3)_2$$

(74) (100 as $CaCO_3$)

OR

1.4 POUNDS OF $CaCO_3$ ALKALINITY ADDED PER POUND $Ca(OH)_2$ ADDED

TABLE 2 - PILOT PLANT:
EIGHT MONTHS HYDRAULIC CHARACTERIZATION

SYSTEM	ITEM	Q - mgd		
		Ave.	Max.	Min.
	Influent	0.21	0.24	0.12
Hydraulic Detention Time - Hours (Based On Q)				
	Prim. Clarifier	1.6	1.3	2.7
High Rate Activated Sludge	Aerator	1.5	1.3	2.5
	Clarifier	1.6	1.3	2.7
Nitrifying Activated Sludge	Aerator	2.8	2.4	4.8
	Clarifier	1.4	1.2	2.4
Denitrifying Activated Sludge	Flash Mixer	0.2	0.1	0.3
	Reactor	1.9	1.6	3.2
	Aerated Channel	0.3	0.3	0.6
	Final Clarifier	2.2	1.9	3.7
Recycle - Percent (Based on Q)				
	High Rate	0.39	0.45	0.31
	Nitrifying	0.56	0.72	0.41
	Denitrifying	0.52	0.68	0.30
Surface Overflow Rates - gpd/sq ft (Based on Q)				
	Primary Clarifier	1140	1280	650
	High Rate Clarifier	1200	1340	680
	Nitrifying Clarifier	1280	1440	730
	Denitrifying Clarifier	750	840	420

cum/day = 3785 mgd
cum/day/sqm = 0.0408 gpd/sq ft

TABLE 3 - INFLUENT AND PRIMARY EFFLUENT QUALITY - mg/l (200 Determinations)

ITEM	Percent Less Than						
	Min.	10	20	50	80	90	Max.
Influent							
SS	8	14	40	80	120	140	340
COD	8	66	102	213	327	391	983
TKN	2.8	6.4	9.2	16.5	23.2	26.4	31.6
NO_2-N	0	0	0	0	TR	TR	1.0
NO_3-N	0	0	0	0	TR	TR	1.7
P	1.7	3.7	4.8	8.0	11.5	13.6	19.0
BOD_5/COD*	0.27			0.44			0.61
Primary Effluent							
SS	2	18	32	52	80	96	180
COD	27	64	86	152	227	250	324
TKN	3.4	7.8	10.1	18.2	24.6	28.6	41.1
NO_2-N	0	0	0	0	TR	TR	0.6
NO_3-N	0	0	0	0	TR	0.2	1.7
P	2.2	3.8	5.0	8.4	11.4	12.8	18.5
BOD_5/COD*	0.26			0.43			0.56

* Minimum, Average and Maximum Monthly Ratio

TABLE 4 - PHOSPHORUS REMOVAL: HIGH RATE ACTIVATED SLUDGE SYSTEM WITH ALUMINUM ADDITION

MONTH	Primary Effluent Phosphorus P	Aluminum Added, Al^{+3}	Biological Phosphorus Removal	Soluble Total P Residual	Al^{+3} Phosphorus Remaining $\frac{B}{A-C}$	Chemical Phosphorus Removal $\frac{A-(C+D)}{B}$	pH
	A	B	C	D	E	F	G
	mg/l	mg/l	mg/l	mg/l	lbAl/lbP	lbP/lbAl	---
NOV	7.5	9.1	0.6	1.4	1.32	0.61	7.6
DEC	11.3	9.8	1.6	3.1	1.01	0.67	7.8
JAN	5.7	5.6	0.9	1.6	1.17	0.57	7.8
FEB	5.7	7.0	0.8	1.5	1.43	0.49	7.8
MAR	9.9	9.4	1.6	1.8	1.13	0.69	7.8
APR	9.6	8.8	1.3	2.4	1.06	0.67	7.7
MAY	7.0	7.5	1.1	1.5	1.27	0.60	7.7
JUN	7.3	5.8	1.0	2.5	0.92	0.83	7.7
AVE.	8.0	7.9	1.1	2.0	1.16	0.64	7.7

TABLE 5 - BIOLOGICAL PERFORMANCE Average, Maximum, Minimum

	High Rate Activated Sludge System			Nitrifying Activated Sludge System			Denitrifying Activated Sludge System		
	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.
Phosphorus Mass Balances, % Accounted For	95	99	83	93	104	71	110	128	97
Nitrogen Mass Balances, % Accounted For	102	114	91	115	121	104	31	58	18
Mean Cell Residence Time, Days	2.4	3.7	1.6	18.7	30.7	14.9	8.0	10.8	5.8
Lb Nonacid Soluble Volatile Solids Produced (Net) Per Lb COD Removed	0.25	0.37	0.17	---	0.05	0.00	0.13	0.18	0.08
Lb Nonacid Soluble Volatile Solids Destroyed Per Day Per Pound Nonacid Soluble MLVSS Under Aeration				---	0.06	0.00			
Nitrogen Removal By Synthesis, $\frac{\text{Lb N Removed}}{\text{Lb COD Removed}}$	0.047	0.060	0.038				0.01	0.02	TR
Phosphorus Removal By Synthesis, $\frac{\text{Lb P Removed}}{\text{Lb COD Removed}}$	0.01*	---	---				TR*	---	---

*Assumed constant from original background measurements (2)

Note: All removals are based upon a soluble effluent analysis, except with the high rate system which used the total pollutant concentrations found in the primary effluent.

TABLE 6 - SOLIDS CHARACTERISTICS:
Average, Maximum, Minimum

ITEM			High Rate Activated Sludge		Nitrifying Activated Sludge		Denitrifying Activated Sludge	
I. REACTOR SOLIDS								
MLSS-mg/l	Ave	Max	3820	4960	3480	4260	4290	5180
		Min		3440		2720		3550
SVI-ml/gm	Ave	Max	59	66	71	89	56	61
		Min		54		62		52
% Volatile Std. Meth.	Ave	Max	49	55	46	50	47	52
		Min		39		42		42
% Nonacid Soluble Volatile	Ave	Max	24	30	27	35	26	34
		Min		17		16		18
N/MLSS	Ave	Max	0.054	0.056	0.042	0.046	0.040	0.045
		Min		0.050		0.038		0.036
P/MLSS	Ave	Max	0.067	0.072	0.069	0.077	0.071	0.075
		Min		0.061		0.062		0.062
II. EFFLUENT SOLIDS								
BOD_5/SS	Ave	Max	0.23	0.31	0.27	0.68	0.45	0.76
		Min		0.10		0.15		0.23
COD/SS	Ave	Max	0.58	0.80	0.51	0.56	0.63	0.89
		Min		0.43		0.40		0.34
N/SS	Ave	Max	0.062	0.100	0.054	0.091	0.058	0.070
		Min		0.047		0.036		0.045
P/SS	Ave	Max	0.051	0.063	0.060	0.079	0.052	0.084
		Min		0.039		0.040		0.035
III. WASTE SOLIDS								
N/TS	Ave	Max	0.049	0.054	NONE		0.019	0.022
		Min		0.039				0.015
P/TS	Ave	Max	0.055	0.063	WASTED		0.065	0.074
		Min		0.045				0.057

TABLE 7 - DENITRIFICATION SYSTEM:
EFFLUENT SUSPENDED SOLIDS

Al^{+3} Added mg/l	pH Adjustment	Anionic Polymer Dosage mg/l	Percent Less Than			Determinations
			20	50	80	
0	No	0	18	24	30	17
0.7	No	0	9	15	20	25
1.3	No	0	13	20	31	25
3.1	Yes	0	20	32	44	50
3.1	Yes	0.4	1	2	8	94

TABLE 8 NOMINAL PERFORMANCE: FINAL FOUR MONTHS OF OPERATION - mg/l

Item	After Final Clarification		After Mixed Media Filtration	
SS	2		0	
COD	21		16	
BOD_5	4.0		0.8	
P	0.6		0.3	
ORG N (TOTAL N)	1.0	= 1.8	0.8	= 1.5
NH_3-N (TOTAL N)	0.0		0.0	
NO_2-N (TOTAL N)	0.0		0.0	
NO_3-N (TOTAL N)	0.8		0.7	

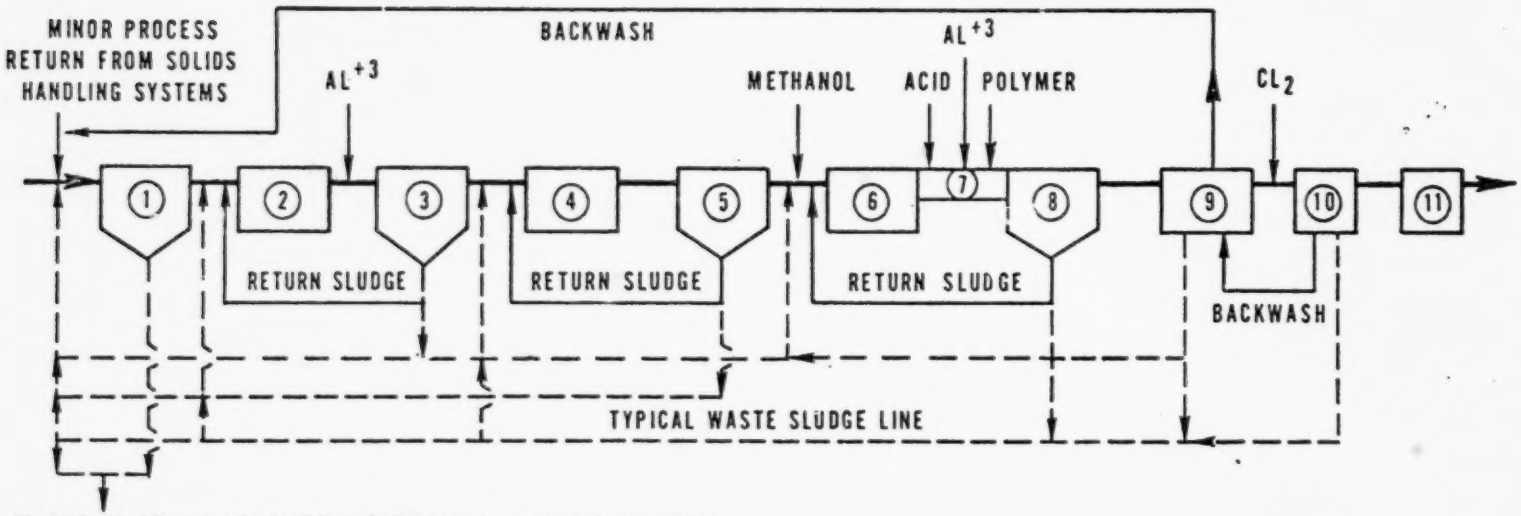
NOTES:

Average $\frac{\text{Total Aluminum Dose}}{\text{Phosphorus Primary Effluent}} = 1.3$ (7.9 mg/l Al^{+3} to first stage) (3.0 mg/l Al^{+3} to third stage)

Average $\frac{\text{Methanol Applied}}{\text{Theoretical Methanol Requirement}} = 1.6$

Average Polymer Dose = 0.4 mg/l

FIGURE 1 - THREE SLUDGE SYSTEM SCHEMATIC



PRIMARY TREATMENT	HIGH RATE ACTIVATED SLUDGE	NITRIFYING ACTIVATED SLUDGE	DENITRIFYING ACTIVATED SLUDGE	POST TREATMENT
(1) CLARIFIER	(2) AERATOR (3) CLARIFIER	(4) AERATOR (5) CLARIFIER	(6) REACTOR (7) AERATED CHANNEL (8) CLARIFIER	(9) MIXED MEDIA FILTER (10) CHLORINE CONTACT (11) POST AERATION
COARSE SETTLEABLE AND FLOTABLE SOLIDS REMOVAL	PROTECTION AND BUFFER FOR NITRIFICATION SYSTEM NITROGEN HYDROLYSIS TO AMMONIA PHOSPHORUS HYDROLYSIS TO PHOSPHATE BIODEGRADABLE CARBON REMOVAL NITROGEN AND PHOSPHORUS REMOVAL BY SYNTHESIS AL^{+3} ADDITION FOR PHOSPHORUS REMOVAL	NITRIFICATION OR REMOVAL OF NITROGENOUS OXYGEN DEMAND POLISH REMOVAL OF BIODEGRADABLE CARBON	DENITRIFICATION OR NITROGEN REMOVAL WITH METHANOL ADDITION AS ACCELERATING SUBSTRATE ACID ADDITION TO ESTABLISH OPTIMUM pH FOR PHOSPHORUS REMOVAL AL^{+3} ADDITION FOR PHOSPHORUS INSOLUBILIZATION POLYMER ADDITION FOR EFFLUENT SOLIDS CONTROL	FILTER FOR SYSTEM BACKUP AND POSITIVE CONTROLS OF EFFLUENT SOLIDS CL_2 ADDITION FOR DISINFECTION POST AERATION FOR FINAL EFFLUENT DISSOLVED OXYGEN

FIGURE 2 - MONTHLY FLOWS AND LIQUID TEMPERATURES

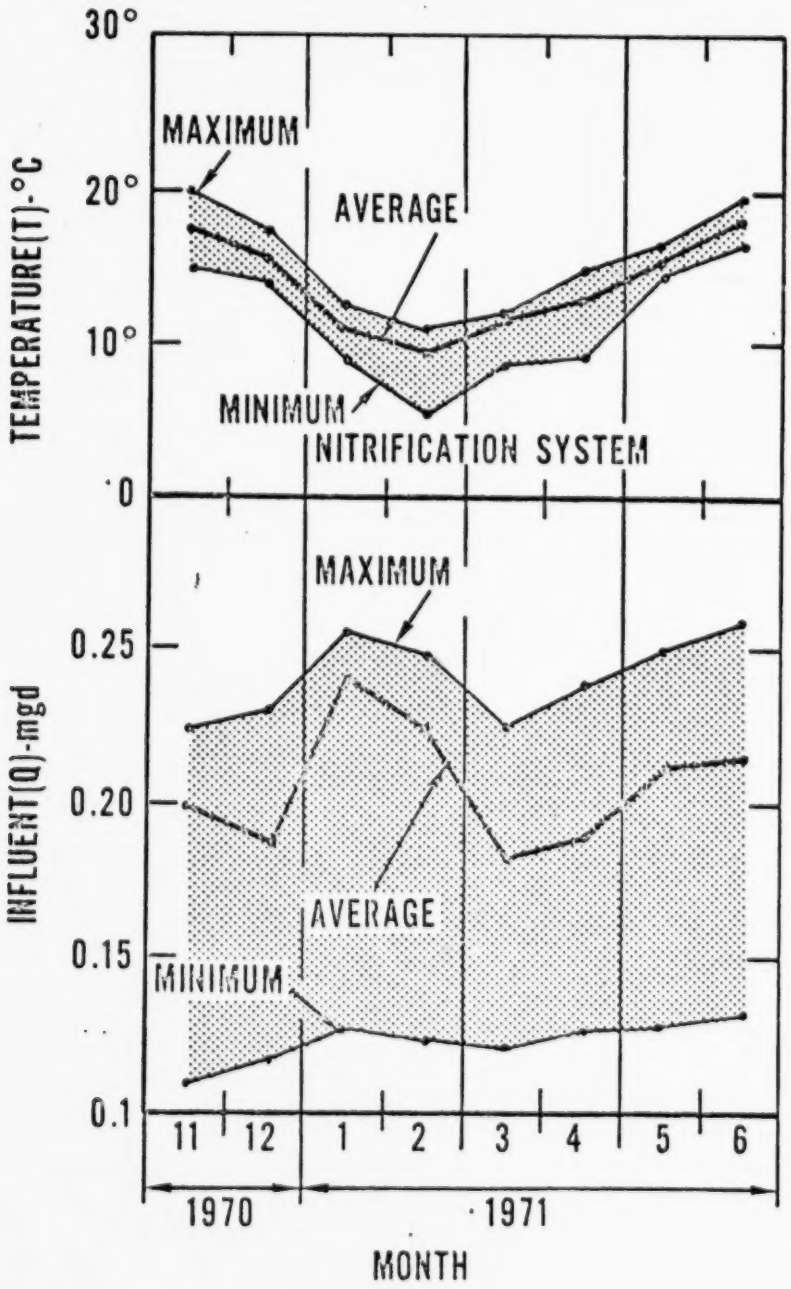


FIGURE 3

pH COMPATABILITY DIAGRAM FOR NITRIFICATION, DENITRIFICATION AND PHOSPHORUS REMOVAL BY LIQUID ALUM ADDITION (NON pH ACCLIMATED CULTURES)

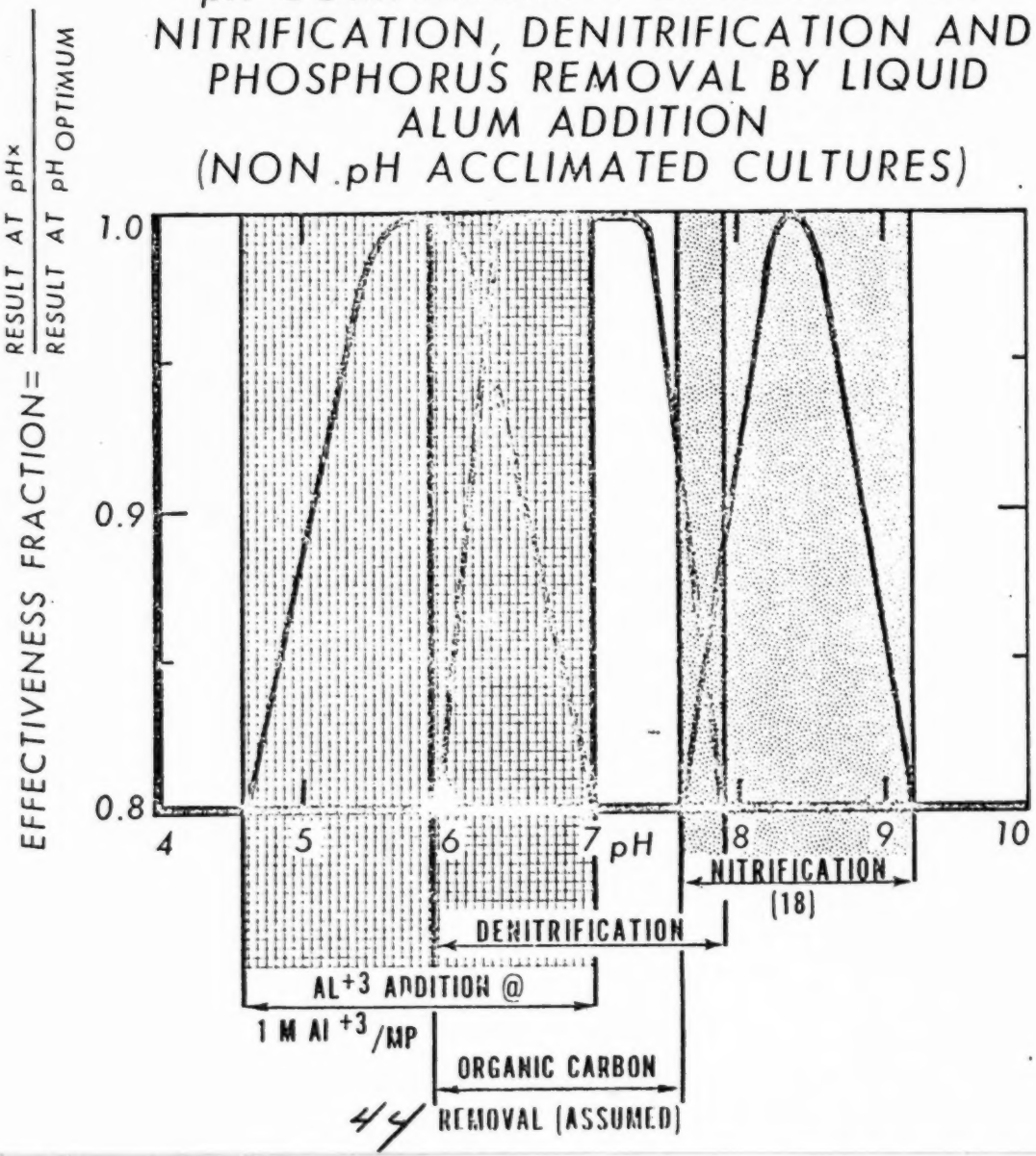


FIGURE 4- NITRIFICATION TEMPERATURE DEPENDENCE

(72 MEASUREMENTS)

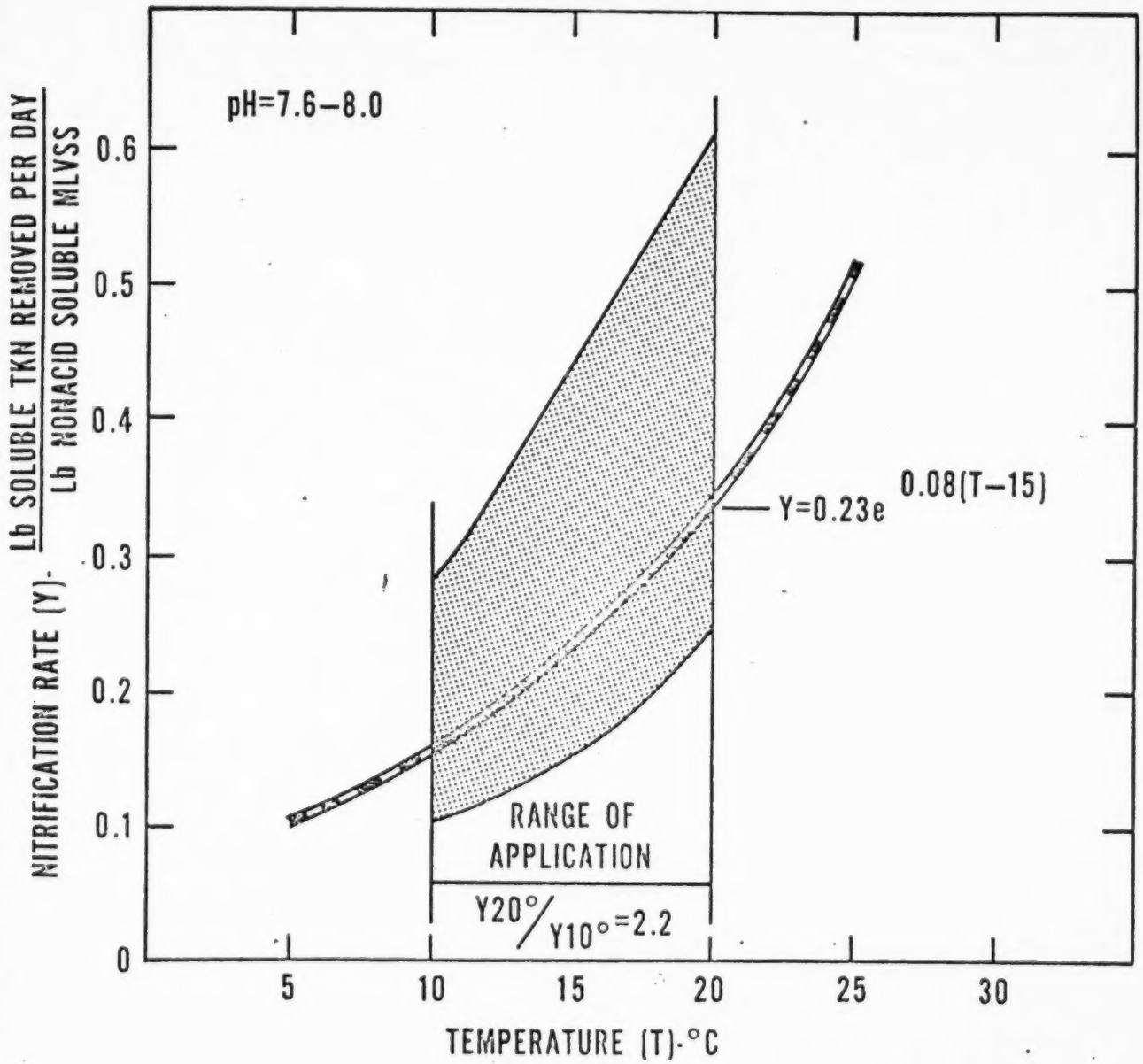


FIGURE 5 - DENITRIFICATION TEMPERATURE DEPENDENCE
(61 MEASUREMENTS)

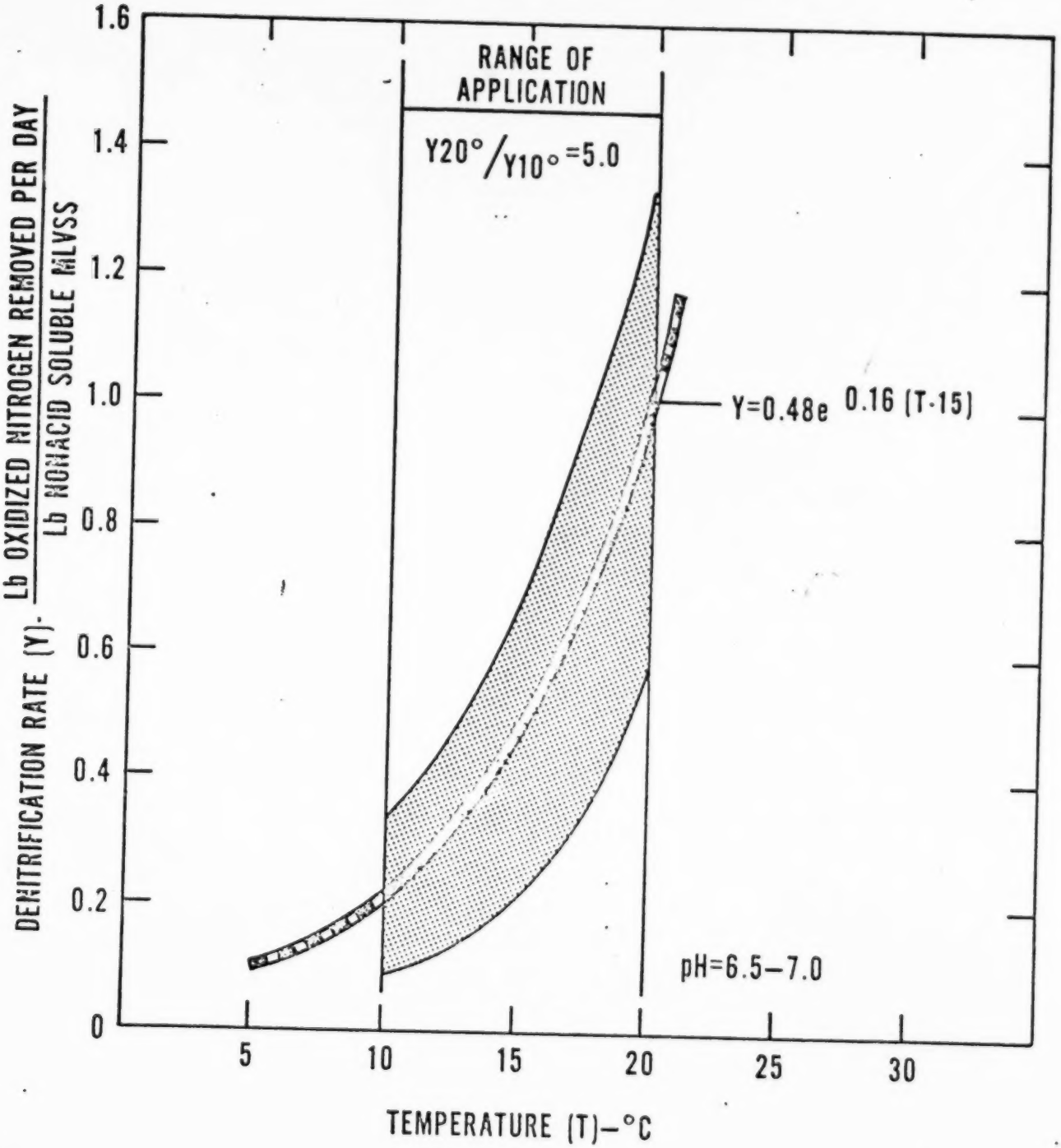
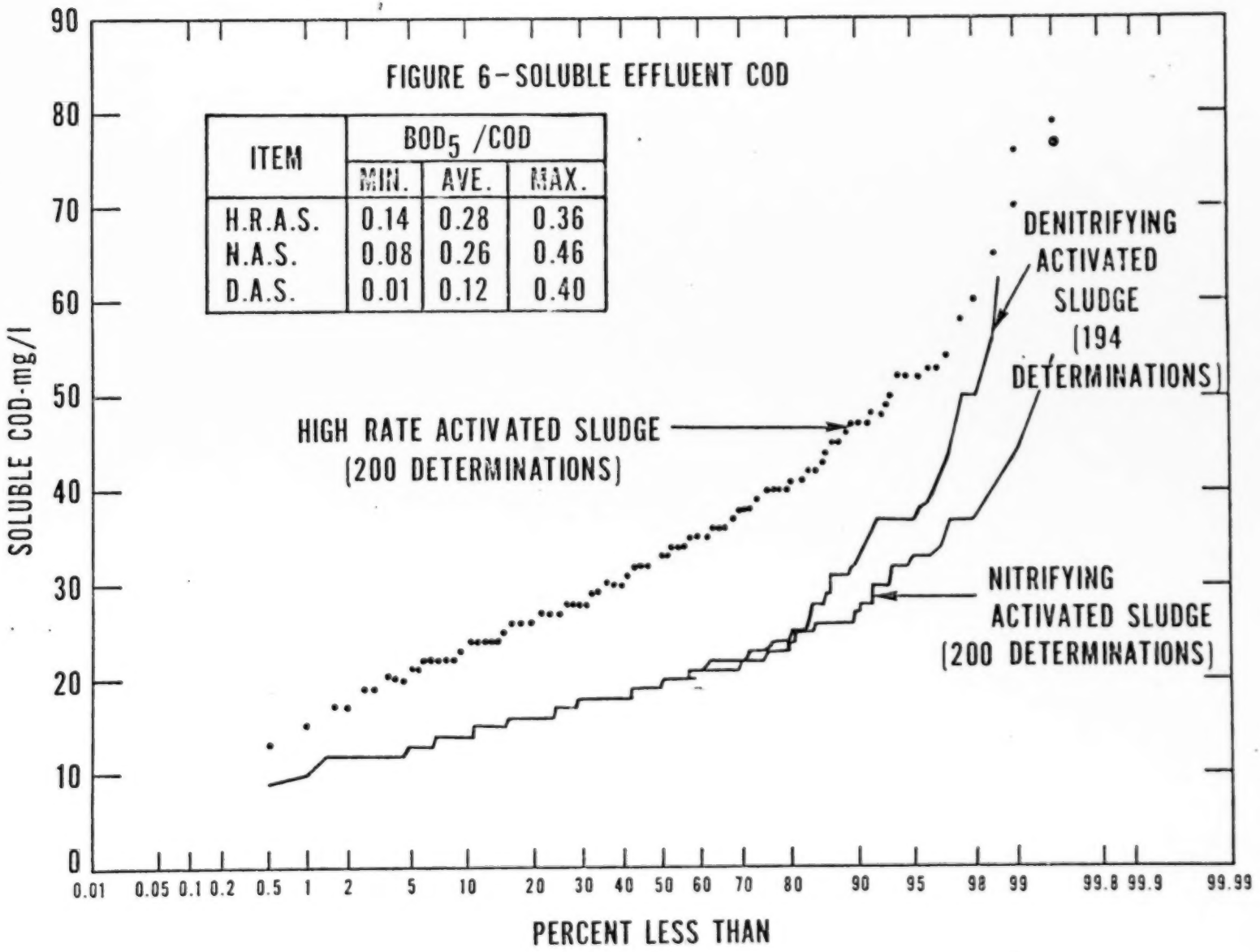


FIGURE 6 – SOLUBLE EFFLUENT COD

ITEM	BOD_5 /COD		
	MIN.	AVE.	MAX.
H.R.A.S.	0.14	0.28	0.36
N.A.S.	0.08	0.26	0.46
D.A.S.	0.01	0.12	0.40



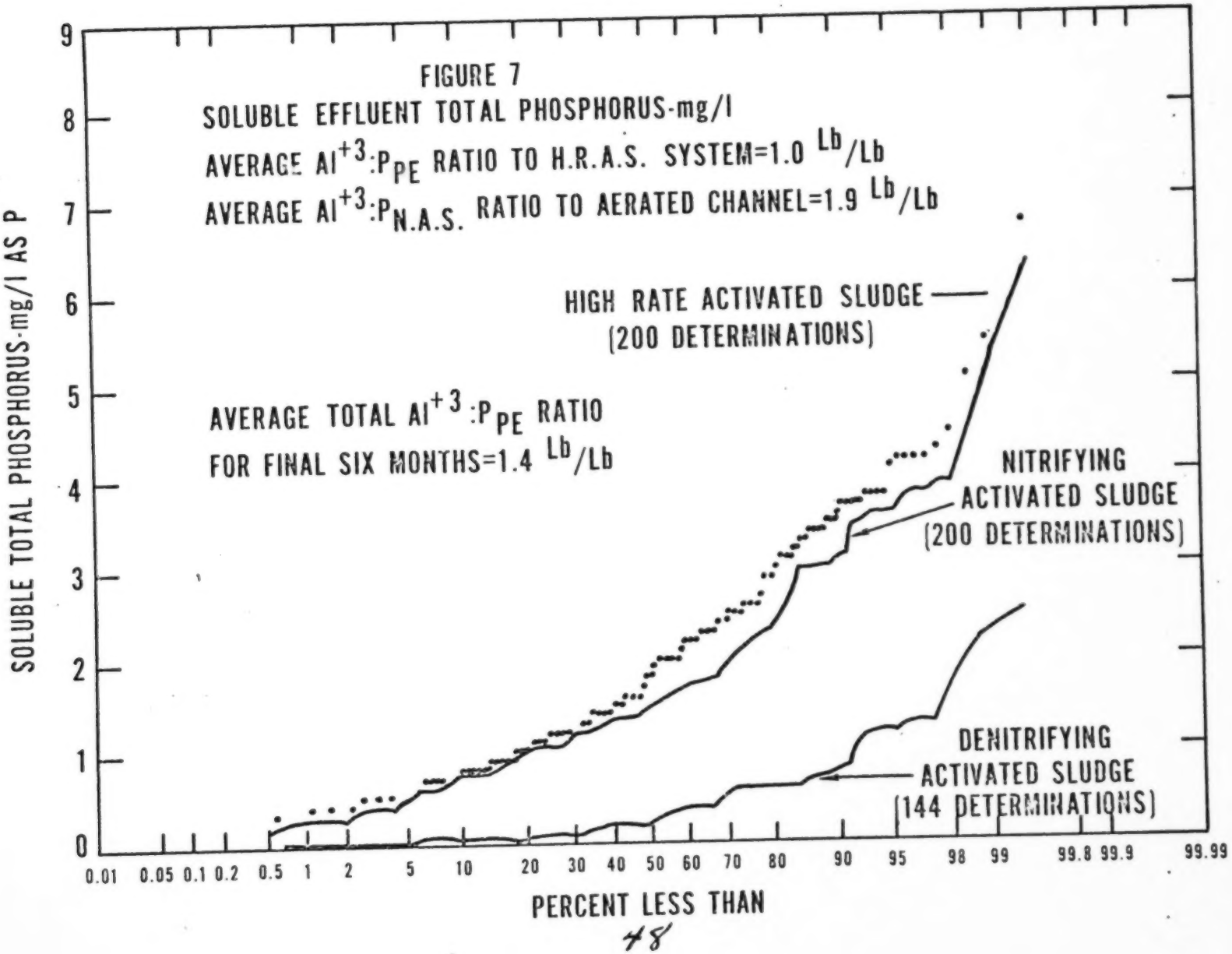


FIGURE 7
SOLUBLE EFFLUENT TOTAL PHOSPHORUS-mg/l
AVERAGE $Al^{+3}:P_{PE}$ RATIO TO H.R.A.S. SYSTEM=1.0 Lb/Lb
AVERAGE $Al^{+3}:P_{N.A.S.}$ RATIO TO AERATED CHANNEL=1.9 Lb/Lb
HIGH RATE ACTIVATED SLUDGE
(200 DETERMINATIONS)
AVERAGE TOTAL $Al^{+3}:P_{PE}$ RATIO
FOR FINAL SIX MONTHS=1.4 Lb/Lb
NITRIFYING
ACTIVATED SLUDGE
(200 DETERMINATIONS)
DENITRIFYING
ACTIVATED SLUDGE
(144 DETERMINATIONS)
SOLUBLE TOTAL PHOSPHORUS-mg/l AS P
0
1
2
3
4
5
6
7
8
9
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT LESS THAN

FIGURE 8- CHEMICAL PHOSPHORUS REMOVAL ENVELOPE: HIGH RATE ACTIVATED SLUDGE SYSTEM

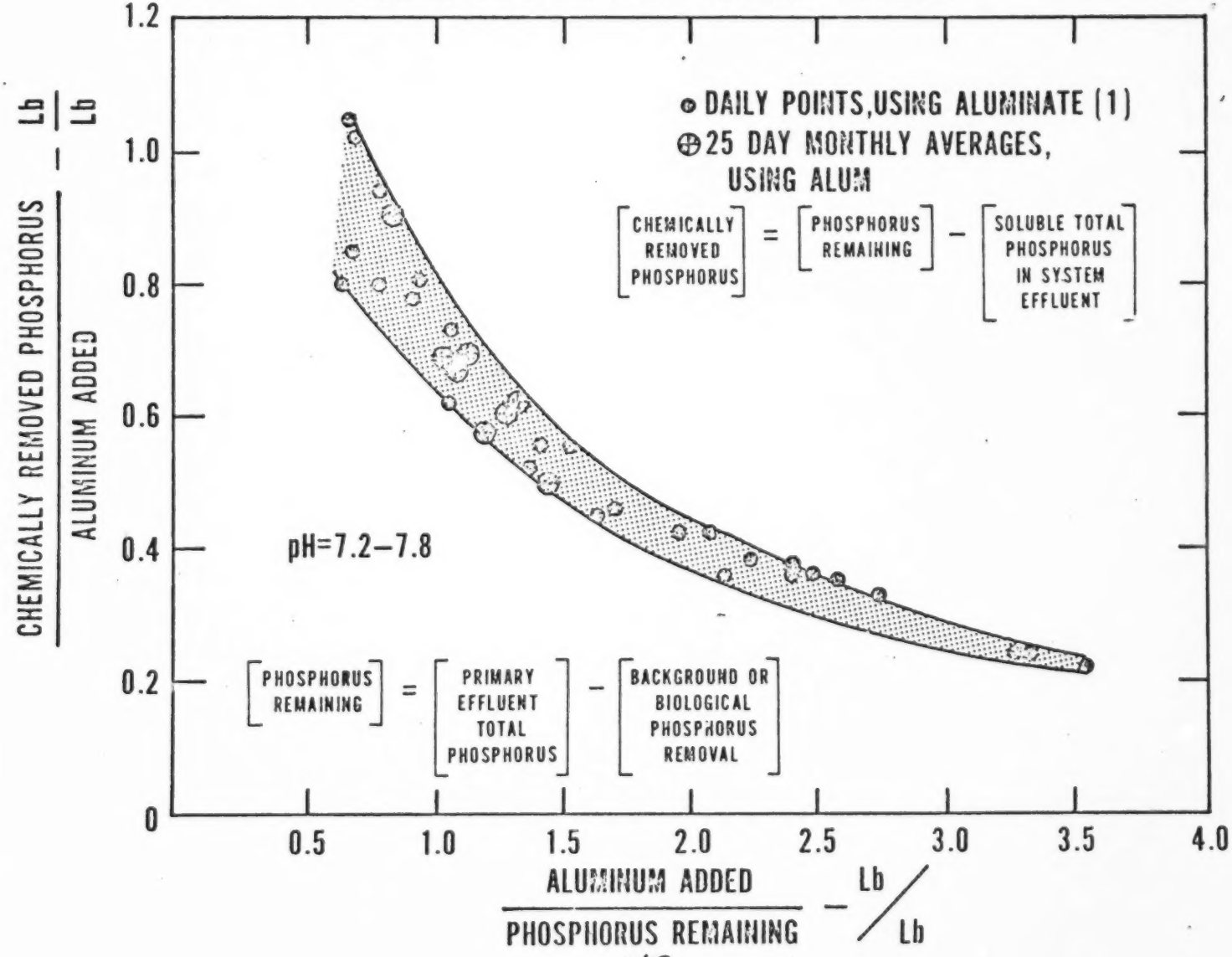


FIGURE 9 - PROJECTED CHEMICAL PHOSPHORUS REMOVAL WITHIN A HIGH RATE ACTIVATED SLUDGE SYSTEM

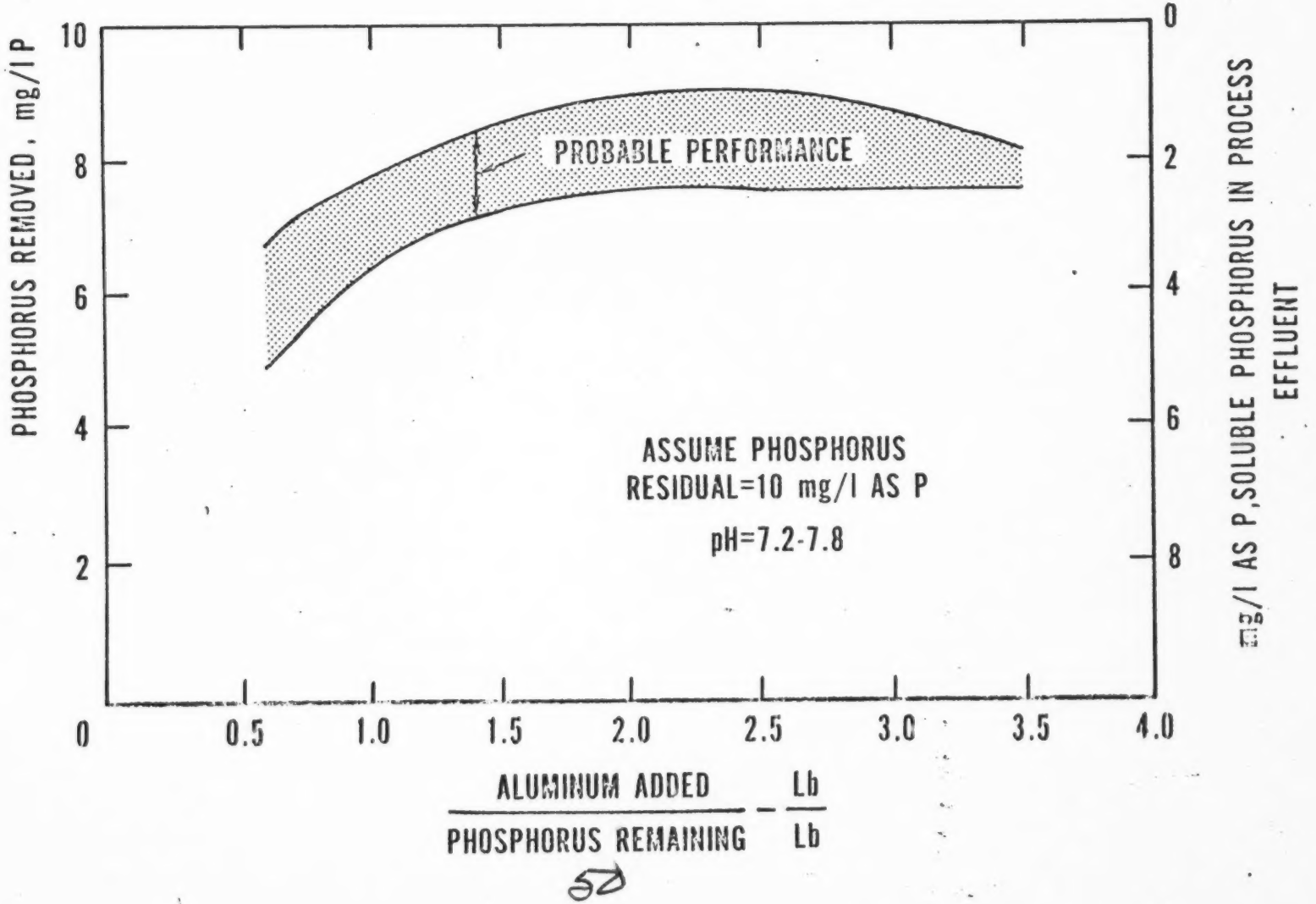
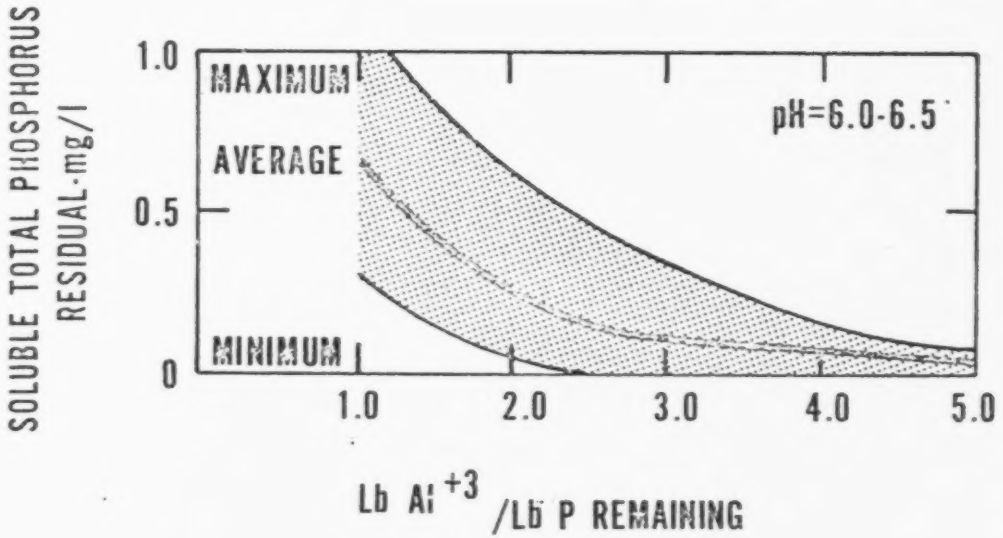


FIGURE 10 - SOLUBLE TOTAL PHOSPHORUS RESIDUAL WITH pH ADJUSTMENT AND ALUMINUM ADDITION



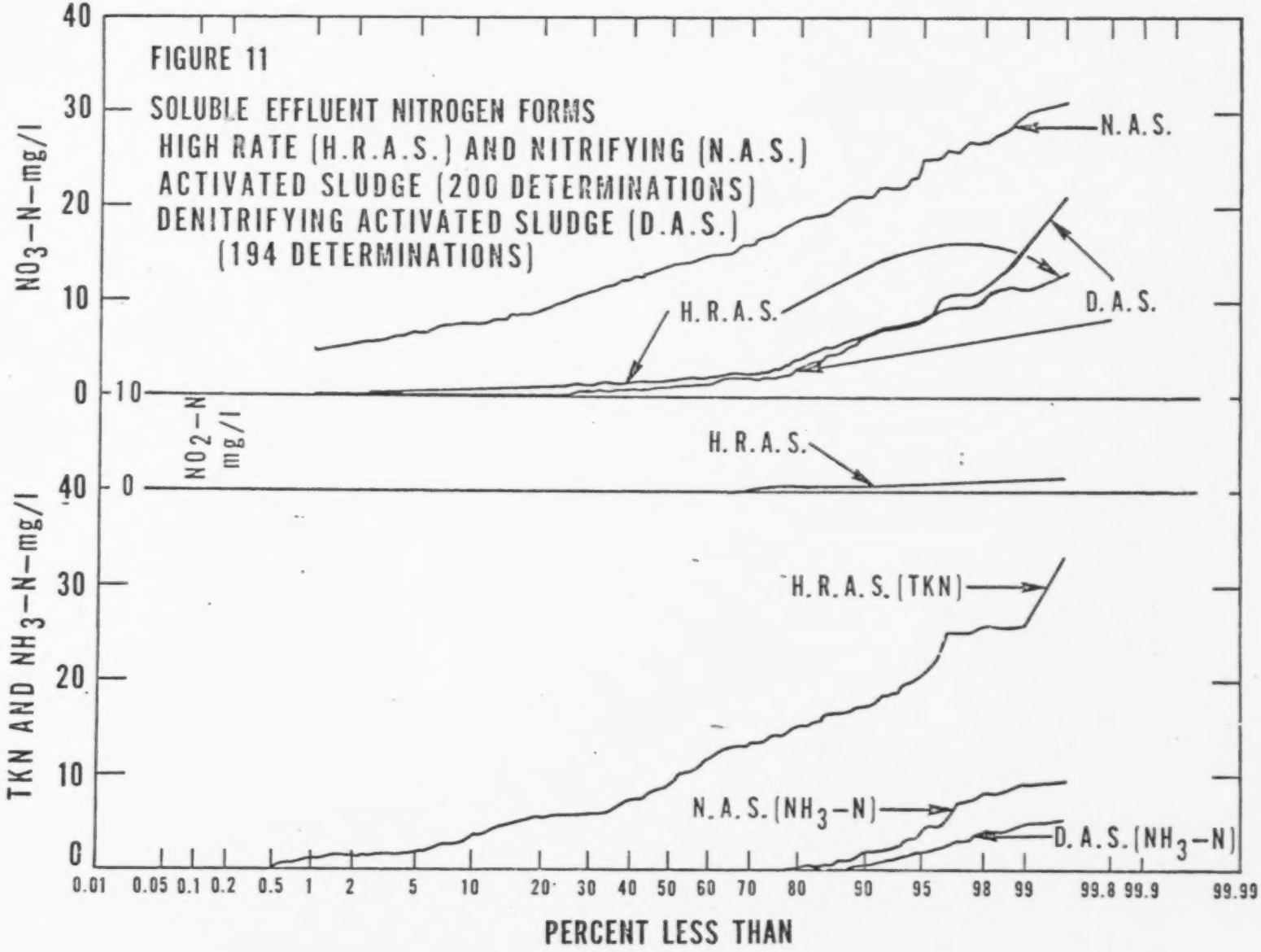


FIGURE 11
SOLUBLE EFFLUENT NITROGEN FORMS
HIGH RATE (H.R.A.S.) AND NITRIFYING (N.A.S.)
ACTIVATED SLUDGE (200 DETERMINATIONS)
DENITRIFYING ACTIVATED SLUDGE (D.A.S.)
(194 DETERMINATIONS)
NO_3–N–mg/l
N.A.S.
H.R.A.S.
D.A.S.
NO_2–N mg/l
H.R.A.S.
TKN AND NH_3–N–mg/l
H.R.A.S. (TKN)
N.A.S. (NH_3–N)
D.A.S. (NH_3–N)
40
30
20
10
0
10
0
40
30
20
10
0
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT LESS THAN

FIGURE 12- PHYSICAL CHARACTERISTICS: HIGH RATE ACTIVATED SLUDGE

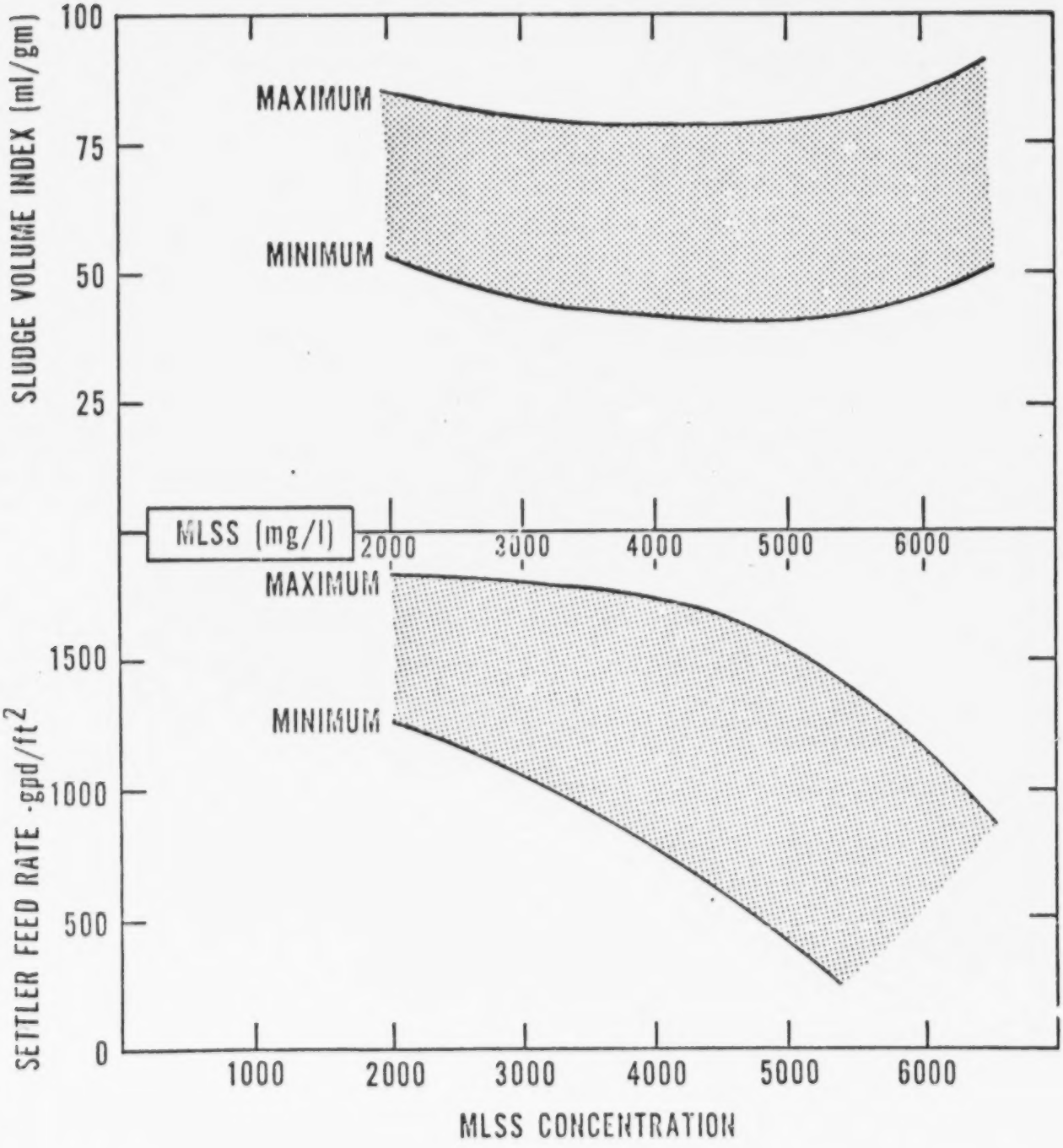


FIGURE 13 – PHYSICAL CHARACTERISTICS:
NITRIFYING ACTIVATED SLUDGE

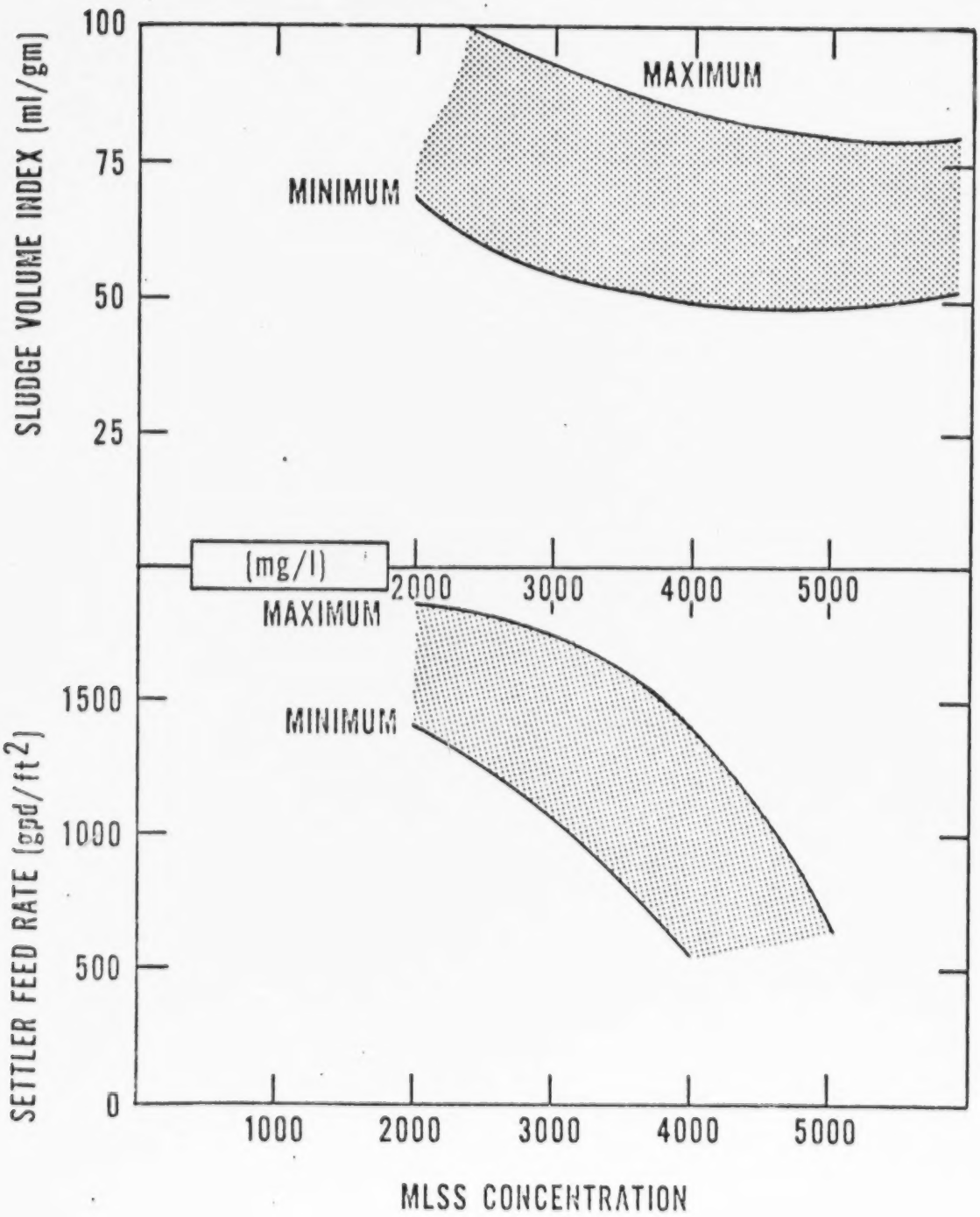
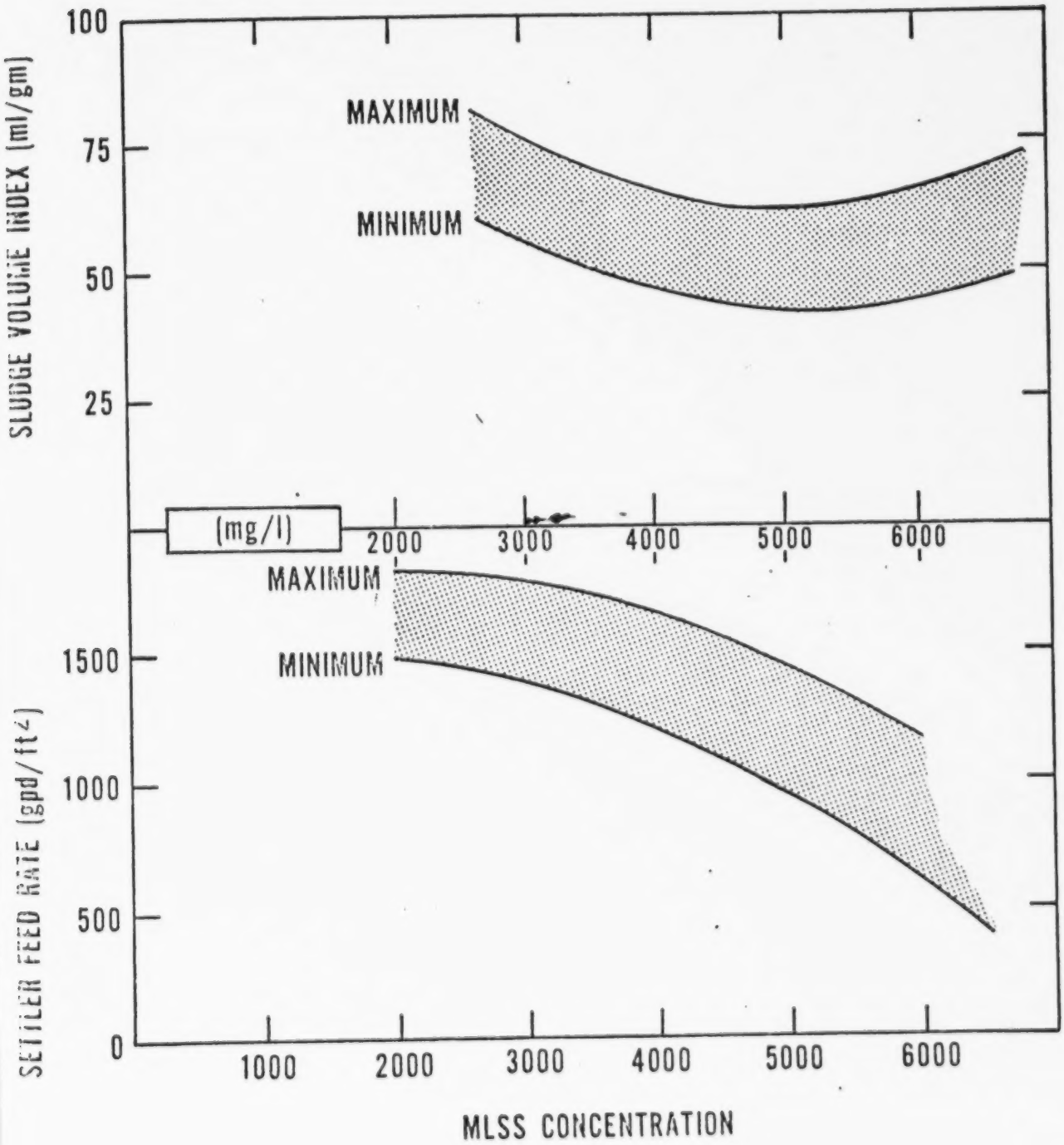


FIGURE 14 – PHYSICAL CHARACTERISTICS: DENITRIFYING ACTIVATED SLUDGE



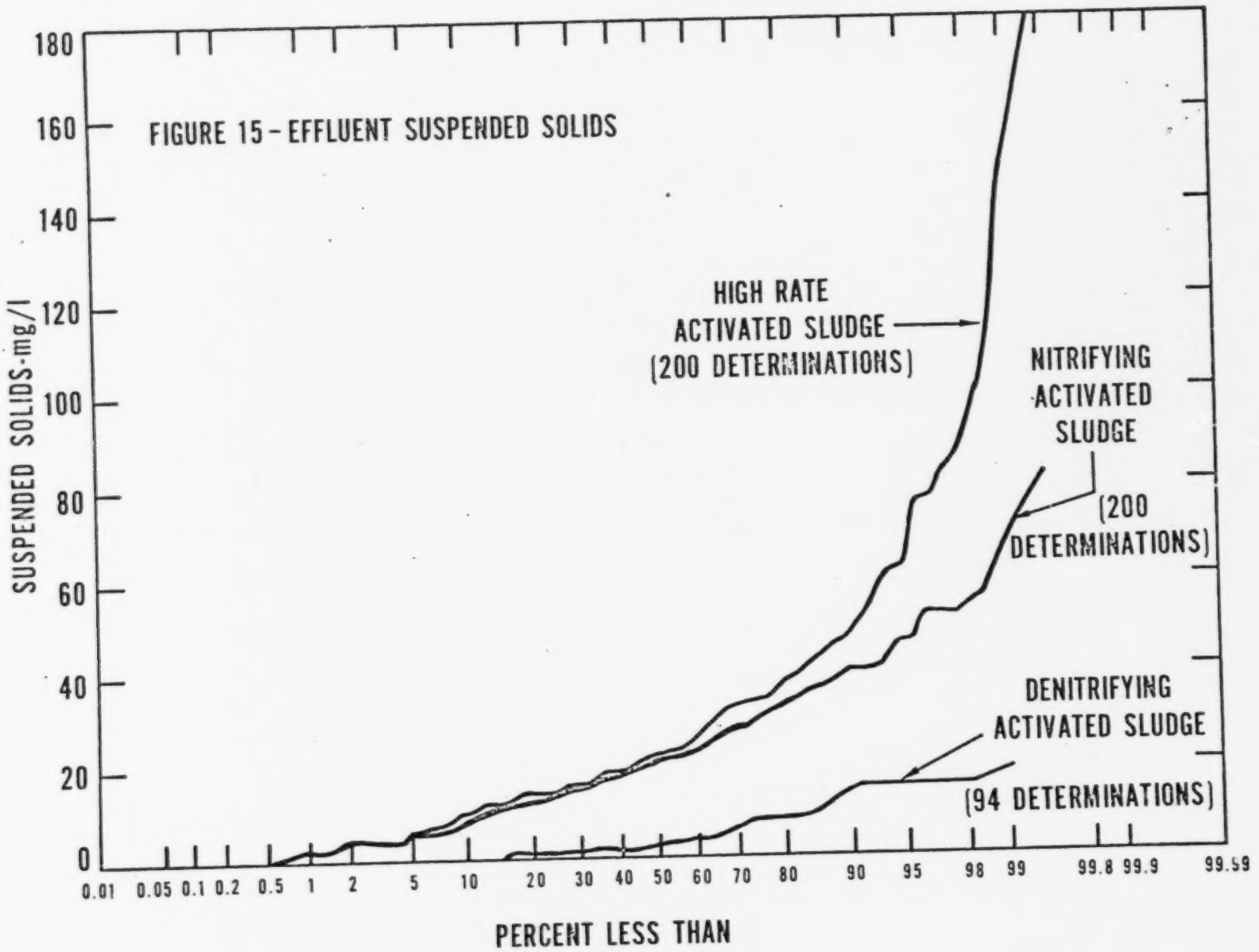


FIGURE 15 - EFFLUENT SUSPENDED SOLIDS
SUSPENDED SOLIDS-mg/l
180
160
140
120
100
80
60
40
20
0
HIGH RATE
ACTIVATED SLUDGE
(200 DETERMINATIONS)
NITRIFYING
ACTIVATED
SLUDGE
(200
DETERMINATIONS)
DENITRIFYING
ACTIVATED SLUDGE
(94 DETERMINATIONS)
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT LESS THAN

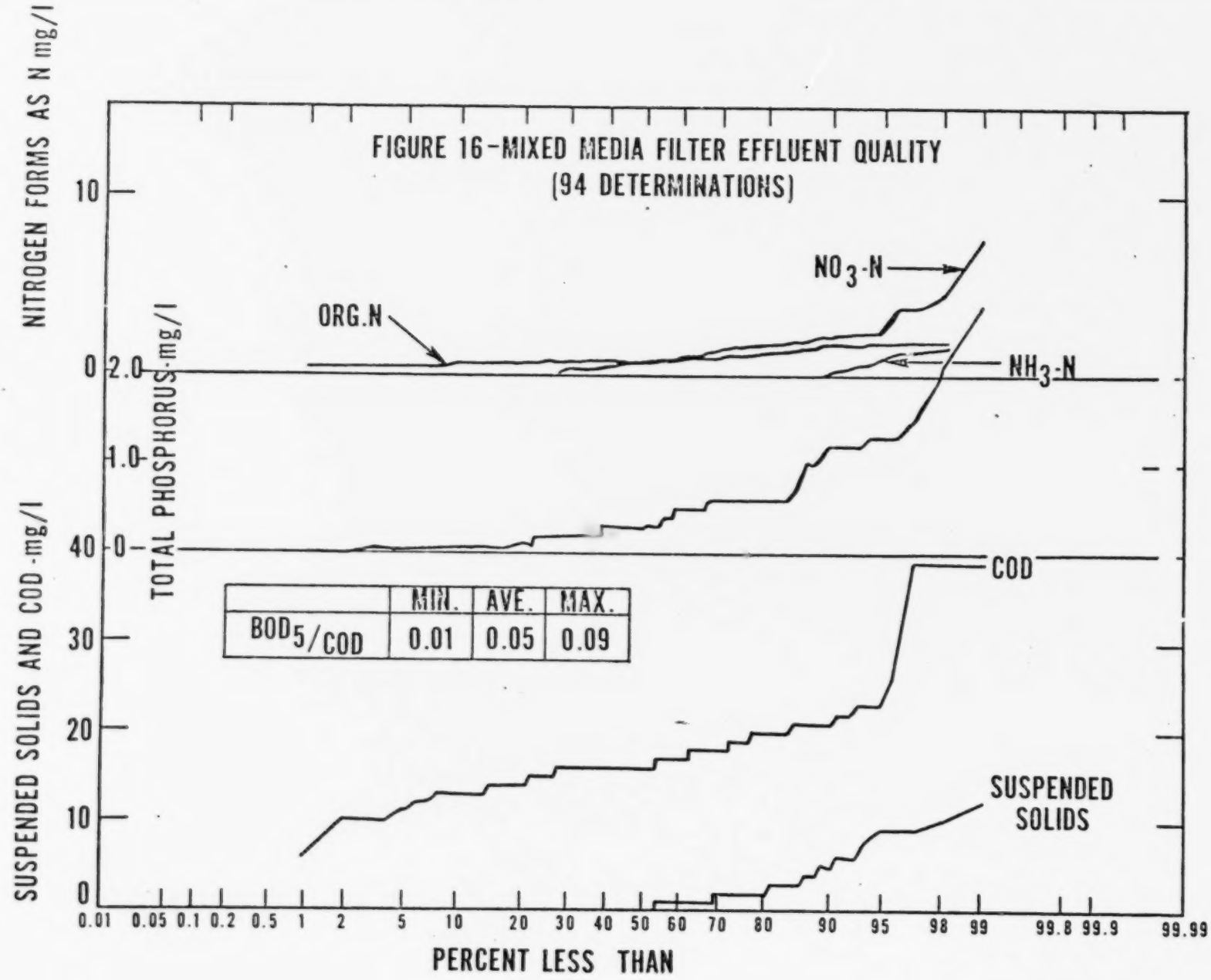


FIGURE 16-MIXED MEDIA FILTER EFFLUENT QUALITY
(94 DETERMINATIONS)
NITROGEN FORMS AS N mg/l
SUSPENDED SOLIDS AND COD-mg/l
TOTAL PHOSPHORUS-mg/l
NO3-N
ORG.N
NH3-N
COD
SUSPENDED SOLIDS
MIN. AVE. MAX.
BOD5/COD 0.01 0.05 0.09
10
0
2.0
1.0
0
40
30
20
10
0
0.01 0.05 0.1 0.2 0.5 1 2 5 10 20 30 40 50 60 70 80 90 95 98 99 99.8 99.9 99.99
PERCENT LESS THAN